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Periphytic algal community structure and their relation with abiotic parameters in rivers of three mining areas of Cote D'ivoire

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Abstract

The periphytic algae on natural substrate and the environmental variables were investigated during dry and rainy season in seven rivers of three mining areas at Tortiya in north, Hiré and Lauzoua in the south of Côte d'Ivoire from November 2017 to January 2019. The environmental and periphytic algae data collected were subjected to a multivariate analysis. A non-metric multidimensional scaling of periphytic algae taxa and a principal component analysis of abiotic parameters were used. The relationship between biodiversity with physical and chemical parameters was determined. The Algal Generic Pollution Index was employed to study the water quality of these rivers. Two hundred and twenty five (225) taxa belonging to seven phyla were recorded. Regarding algal groups, green algae (Chlorophyta) were most diverse (69 taxa) followed by Euglenophyta, Bacillariophyta (Diatoms), Cyanobacteria with respectively 60, 54 and 44 taxa. Other groups consisted of at least 2 taxa from Dinophyta, 4 and 3 taxa respectivily of Ocrophyta and Rhodophyta. Manganese mining area (Lauzoua) recorded highest diversity with 216 taxa. It is followed by Tortiya with 202 taxa. Gold mining area (Hiré) recorded lowest diversity with 195 taxa. The stations from gold mining had lowers values of biotic index and biovolume but highest values of Palmer's index than stations from diamond and manganese mining areas. This would therefore be the environment most disturbed by gold mining activity. Manganese and diamond mining at Lauzoua and Tortiya respectively have a lesser effect on the organisation of the periphytic algal community.

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Introduction

Rivers exert an important rôle in the survival strategies for human populations and their economic activities. For local community, mining exploitation has been one of the most important economic activities developed around rivers (Yoboué, 2017). In Côte d'Ivoire, three regions (Tortiya, Hiré and Lauzoua) among many others are subjected to mining. There are diamond, gold and manganese mining exploitation respectively at Tortiya, Hiré and Lauzoua. Mining activities can change the intensity, physicals and chemicals parameters of the water and competitive relationships between organisms for available resources (Zapata *et al.*, 2007; N'guessan *et al.*, 2020).

Changes in aquatic ecosystems due to disturbances work as environmental filters that alter the relationships between species and the environment and are key factors in understanding patterns of community distribution and establishment.

Mining activity degrades mostly the aquatic ecosystem and has been considered to have serious effects on water quality and quantity due to mining wastes and the ecological impairment of habitats (Wright and Ryan, 2016). Because of these impacts the vulnerability of these rivers and their importance as water supply for human needs make it essential to implement monitoring plans for the protection of water resources. Hence, the environmental monitoring in catchments of Côte d'Ivoire has been addressed only by physical and chemical parameters of water quality and rarely with biological criteria (N'guessan *et al.*, 2020). The best method to better manage aquatic ecosystems comes from informations relating to the conditions (health) of the organisms they contain. Because of the brief generation replication times of periphytic algae and their quickly answer to seasonal and environmental changes, they can be considered good indicators of changes (abiotic factors and biotic interactions) in aquatic systems (Reynolds, 1998; Soininen, 2012; Collins *et al.*, 2014). In aquatic environments, periphytic algae are important for carbon sequestration, primary productivity, nutrient cycling (Reynolds, 2006) and food web interactions (Stevenson, 1996). Their establishment in these environments is the outcome of complex interactions between many factors, such as disturbances (Biggs *et al.*, 1998), nutrient availability (Ferragut and Bicudo, 2010; Dunck *et al.*, 2013), light (Tuji, 2000) and hydrodynamics (Algarte *et al.*, 2009). Although this community is frequently subjected to adverse physical conditions such as high stream velocities or high turbidity levels (Sami *et al.*, 2011).

Most of work about algae on rivers in Côte d'Ivoire has been carried out in the southern part of the country (Ouattara, 2000; Niamien-Ébrottié *et al.*, 2008; Salla, 2015) and have only shown the impacts of the anthropogenic activities and namely, those of the agriculture on the algae proliferation. No study has evaluated the impacts of mining activities on periphytic algae communities. In this regard, this study aims to analyse the effect of mining (diamond, gold and manganese) exploitation on periphytic algae communities of rivers from three mining areas: Diamond mining area (Tortiya), gold mining area (Hiré) and manganese mining area (Lauzoua).

Materials and methods

Study area and sampling stations characteristics

The study was conducted at three mining areas in Côte d'Ivoire. One zone from north (Tortiya: diamond mining) and the two others were located in south (Hiré: gold mining and Liuzhou: manganese mining). The georgrapical position of sampling stations was illustrated in Fig. 1. The sampling stations choices were focused on the accessibility, permanence of the watercourse and taking into account the degree of disturbance of station by mining activities. Sampling stations were also selected to evaluate the impact of others anthropic activities on water quality and subsequently periphytic algae communities. Thus a total of eight (8) stations were selected from seven (7) rivers. Three rivers were sampled in gold mining area (Gbloh, Tributary Gbloh and Tchindégri) and three in manganese mining area (Dougodou, Tributary Dougodou and N'têko).

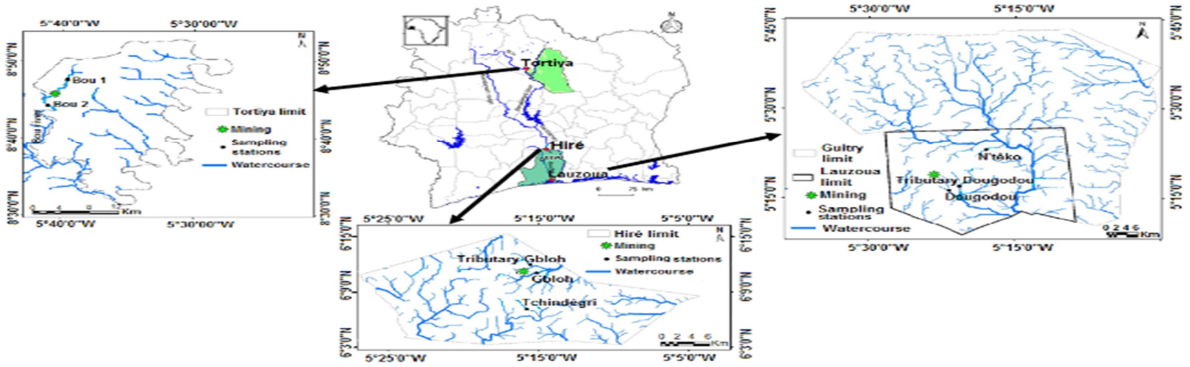

Fig. 1. Maps of studies areas showing the different sampling stations

Table 1. Geographic coordinates descriptions and characteristics of sampling stations from mining areas

Localities	Sampling stations	Characteristics of sampling stations				
		X	Y	Land occupation	Nature of substrate	Canopy (%)
TORTIYA (Area of Diamond exploitation)	BOU 1 (B1)	5°39'43"	8°47'0"	Cashew plantation, agriculture Fishing, no mining activity	Clay and vase	0
	BOU 2 (B2)	5°41'43"	8°45'0"	Diamond mining, fishing, washing car and presence of beef	Gravels	0
HIRE (Area of Gold exploitation)	GBLOH (GB)	5°15'17"	6°11'08"	Artisanal and industry gold activities, farming	Sand and clay	15
	TRIBUTARY GBLOH (TG)	5°15'69"	6°12'0"	Gold industry activity, teak, tomatoes and cocoa plantations	Sand. vase and clay	10
	TCHINDEGRI (TC)	5°16'03"	6°08'32"	Abandoned gold mining activity and cocoa plantations	Vase and plant debris	95
LAUZOUA (Area of Manganese exploitation)	DOUGODOU (DO)	5°21'82"	5°16'36"	Manganese mining, cocoa plantations	Sand	15
	TRIBUTARY DOUGODOU (TD)	5°20'45"	5°16'63"	Manganese mining, cocoa plantations, rice field	Sand and gravels	0
	N'TEKO (NT)	5°18'55"	5°22'09"	No mining activity, on roadside, cocoa plantations	Sand and clay	80

In Diamond's locality, only Bou stream was sampled. In each river, one station has been defined, except Bou stream where two stations have been defined according to the upstream (Bou 1) and downstream (Bou 2) gradient. The characteristics of each sampling station are presented below in Table 1.

Environmental variables

The samples were collected during eight campaigns from november 2017 to january 2019. At each sampling station, the environmental features such as water temperature (Temp), hydrogen potential (pH), conductivity (Cond), dissolved oxygen (Do), turbidity (Turb), total dissolved solids (TDS) and flow water (Flow) were recorded *in situ* between 7:00 and 11:00 a.m. The pH and temperature were determined with a pH meter type HANNA HI991001. Conductivity and total dissolved solids were determined using a multi-parameter HANNA HI98703. Dissolved oxygen was measured with an oximeter type HANNA HI9146. For nutrients, 1 liter of water sample was fixed with acid, stored in a 4 °C incubator and transported back to the laboratory to measure the concentrations of nitrate (Nitra), ammonium (Amo) and phosphate (Phos) following the methods established by the American Public Health Association (APHA, 2005).

Sampling and counting algae

Periphitic algae samples were collected from november 2017 to january 2019. From the natural substrata the sample was obtained by cutting off a plant fragment (length 30 cm) in the water column and placed in a plastic bottle and then adding distilled water. Periphytic algae were separated from the plant samples by shaking the sealed bottle vigorously during 5 minutes. Next the suspension was filtered through a 300 µm mesh to avoid contamination of small plant fragments or invertebrates. From this sample, 100 mL of periphitic algae sample was fixed with 1 mL lugol's solution and then with five drops of 5 % formaldehyde solution.

Identification to species level was based on the key of Amossé (1970); Prescott *et al.* (1975); Komárek and Fott (1983) ; Couté and Iltis (1985) ; Krammer and Lange-Bertalot (1986, 1988, 1991) ; Huber-Pestalozzi (1995) and Komárek and Anagnostidis (1999, 2005). For identification of diatoms, frustules were cleaned with concentrated chlorodric acid and nitric acid.

An aliquot (5 mL) was taken from the subsample and placed in 5 mL Utermöhl counting chamber. After settling at least algal densities cellulars were counted in transects. All cellulars of colonial algae were counted. Counting and identification were performed at 400× magnification under an inverted microscope.

The density was estimated by employing an inverted microscope according to Utermöhl (1958). In order to calculate biomass, cellular numbers were converted to biovolume using geometric or combined forms formulae. Biovolume was obtained by geometric approximation (Hillebrand *et al.*, 1999; Ouattara, 2000; Tsarenko *et al.*, 2005, 2009, 2011) and was calculated by multiplying each species density by its average volume and the result was expressed by $\mu m^3/cm^2$.

Data analyses

Principal Component Analysis (PCA) using the Euclidean distance was performed to ordinate sampling stations according to environmental variables. The software R 3.1.3 (Ishaka and Gentleman, 1996) with the package ade 4 (Thioulouse *et al.*, 1997) was used for the analyses. Hierarchical Classification Analysis (HCA), based on Ward's method, was used to cluster the sampling stations on the basis of their similarities in terms of abiotic parameters and the results are presented in the form of a dendrogram (Dufrêne, 1992). The structural properties of the periphytic algae community at each sampling station were used to characterize by the Shannon-Weiner index (H') and Equitability index (E).

Palmer (1969) Algal Genus Pollution Index was employed to study the water quality of rivers from three mining areas. According to Palmer's Algal Pollution Index values between 0-10 indicate lack of organic pollution, 10-15 moderate pollution, 15-20 probable high organic pollution and 20 and above as confirmed high organic pollution.

Variations in abiotic parameters and biotic index between stations into a locality were evaluated using Kruskal-Wallis and Mann-Whitney test. The significance threshold was $p < 0.05$. The compositional dissimilarity of periphytic algae abundance of biovolume was examined with a non-metric multidimensional scaling (nMDS) based on the Bray-Curtis index (Quinn and Keough, 2002). An ANOSIM was used to determine whether the compositional dissimilarity was greater among than within localities and the contribution of the periphytic algae composition to the dissimilarity was subsequently established using a SIMPER analysis (Quinn and Keough, 2002). Both NMDS and ANOSIM analyses were performed using PRIMER (Plymouth Routines in Multivariate Ecological Research) 6 software (Clarke and Warwick, 2001). The patterns of biovolume abundance diversity and compositional dissimilarity were discussed with respect to environmental parameters. Variation in periphytic algae biovolume data was directly examined with environmental variables by a ReDondance Analysis (RDA) after ensuring that this technique was appropriate. The main taxa are those with a relative biovolume of at least 2% at least one station and present in more than 2 surveys (Chomérat, 2005). In order to reduce the amplitude of the fluctuations and ensure linearity of the relationships between the biotic variables, periphytic algae biovolume data (X) were subjected to a logarithmic transformation and then expressed as log

(X+1) (Palm, 1990). This analysis was performed using CANOCO 4.5 software (Ter Braak and Smilauer, 2002). RDA has made it possible to summarize the different relationships between periphytic algae biovolume data with environment data. The relevance of this analysis was first verified using a Monte Carlo permutation test (Manly, 1994) on 199 random permutations.

Results

Spatio-seasonal variations of abiotic factors

Spatio-seasonal variations of physico-chemicals parameters (temperature, electrical conductivity, pH, turbidity, total dissolved solids, dissolved oxygen, flow water velocity, nitrate, phosphate and ammonium) measured at the 8 sampling stations during research period are summarized in Table 2. The lowest temperature (25°C) was measured at N'teko (manganese mining area), while the highest temperature was 31.2 °C at Bou 1 (diamond mining area) during rainy season. Electrical conductivity varied between 110.1 (Bou 2 in dry season) and 1452.5 µS/cm (Tributary Gbloh in rainy season).The values of pH were ranged from 6.58 (N'teko) in dry season to 7.56 (Tributary Gbloh) in rainy season. Dissolved oxygen oscillated from 3.19 (Dougodou in dry season) to 10.45 mg/L (Tchindégri in dry season) respectively at manganese mining area (Lauzoua) and gold mining area (Hiré). Turbidity values were fluctuated between 9.84 (Dougodou in dry season) at Lauzoua to 245.84 UNT (Gbloh in dry season) at Hiré. The lowest (53.61) and highest (493.75) values of the total dissolved solids were observed respectively at Dougodou (manganese mining area) and Tributary Gbloh (gold mining area) during dry season. The values of flow water velocity were ranged from 0.30 m^3/s (Tributary Dougodou during dry season) to 0.97 m^3/s (Bou 2 during rainy season) respectively at manganese mining area and diamond mining area.

Electrical conductivity and turbidity did not vary significantly between stations of diamond mining area (Mann-Whitney test, $p > 0.05$). However, these parameters were statistically higher (Mann-Whitney test, $p < 0.05$) respectively in Tributary Gbloh and Gbloh stations at gold mining locality. Turbidity was significantly higher at Tributary Dougodou in manganese locality. The temperature values recorded at N'têko were significantly lower than those obtained at Dougodou station in manganese mining area (Mann-Whitney test, $p < 0.05$). Concerning turbidity, the values observed at manganese mining area differ significantly from one station to another (Mann-Whitney test, $p < 0.05$). Regarding total dissolved solids, the values noted at gold mining area were significantly different between the stations of this locality (Mann-Whitney test, $p < 0.05$).

Nitrates values fluctuated from 3.76 (Tributary Dougodou) to 53.23 mg/L (Tributary Gbloh) in rainy season respectively from manganese and gold mining areas. Ammonium concentrations varied from 0.30 (N'teko at rainy season) to 3.48 mg/L (Tributary Gbloh in rainy season) respectively at manganese and gold mining areas. Phosphate concentrations oscillated from 0.24 (Bou 1 at dry season) in diamond mining area to 2.22 mg/L (N'têko at rainy season) in manganese mining areas.

Concerning nutrients concentrations, the nitrates values obtained were significantly lower at Gbloh in gold mining area (Mann-Whitney test, $p < 0.05$). Ammonium and phosphate values were significantly higher at Tributary Gbloh in gold mining area. At the seasonal level, no significant variation was observed within a station in the different mining localities. Ammonium values in N'têko (manganese mining area) are significantly lower during the rainy season.

Abiotic differentiation of sampling stations

Principal Component Analysis (Fig. 2A) performed on the physical and chemical variables (73.86 % of cumulated variance associated with two first principal components) showed a clear discrimination between the sampling stations. First axis associated positively with Turbidity (Turb), conductivity (CND), total dissolved solids (TDS), potential hydrogen (pH), dissolved oxygen (Do), ammonium (Am), nitrate (Nitra) and phosphate (Phos) supports a clear mineralization gradient (Fig. 2B).

Table 2. Physico-chemical variables related to the water in the sampling stations in Diamond, gold and manganese mining areas during sampling period. B1 : Bou 1, B2 : Bou 2, GB : Gbloh, TG : Tributary Gbloh, TC : Tchindégri, DO : Dougodou, TD : Tributary Dougodou and NT : N'teko. DS : Dry season, RS : Rainy season, ND : Not determined, the letter in common do not differ significantly between a locality from one station to another (Tortiya : Mann-Whitney test; $p > 0.05$; Hiré and Lauzoua : Kruskal-Wallis, $p > 0.05$) and from one season to another between a same station (Mann-Whitney test, $p > 0.05$).

Environnement variable	Abreviation	Climatic season	Diamond mining area (TORTIYA)		Gold mining area (HIRE)			Manganese mining area (LAUZOUA)		
			B1	B2	GB	TG	TC	DO	TD	NT
Water temperature (°C)	T	DS	28.65^{a}	27.81^{a}	26.4^{a}	27.35^{a}	26.98^{a}	26.95^{a}	27.05^{a}	26.5^{a}
		RS	31.2^{a}	27.7^{a}	26.75^{a}	27.75^{a}	25.83^{a}	27.93^{a}	26.75^{a}	25^{a}
Turbidity (UNT)	Turb	DS	49.89^{a}	90.58^{a}	245.84^{a}	142.19^{a}	89.17^{a}	9.84^{a}	41.1^{b}	35.94^{c}
		RS	78.64^{a}	43.31^{a}	72.13^{a}	138.38^{a}	72.24^{a}	16.94^{a}	93.06^{b}	28^{c}
Conductivity (µS/cm)	CND	DS	158.19^{a}	110.1^{a}	487.13^{a}	1299.38^{a}	195.2^{a}	171.78^{a}	189.25^{a}	202.35^{a}
		RS	137.05^{a}	185.15^{a}	691.5^{a}	1452.5^{b}	186.93^{a}	223.95^{a}	243.45^{a}	176.5^{a}
Water flow (m^3/s)	Q	DS	0.47^{a}	0.83^{b}	0.68^{a}	0.60^{a}	0.38^{a}	0.31^{a}	0.30^{a}	ND
		RS	0.58^{a}	0.97^{b}	0.75^{a}	0.67^{a}	0.66^{a}	0.64^{b}	0.66^{b}	ND
Potential Hydrogen	pH	DS	6.76^{a}	6.84^{a}	6.85^{a}	7.29^{a}	6.80^{a}	7.03^{a}	6.7^{a}	6.58^{a}
		RS	6.96^{a}	6.86^{a}	7.21^{a}	7.56^{a}	7.17^{a}	6.99^{a}	7.09^{a}	7.22^{a}
Dissoled oxygen (mg/L)	Do	DS	5.54^{a}	6.11^{a}	5.15^{a}	8.00^{a}	10.45^{a}	3.19^{a}	5.34^{a}	3.30^{a}
		RS	5.07^{a}	4.57^{a}	6.66^{a}	7.60^{a}	8.24^{a}	6.81^{b}	3.94^{a}	5.93^{a}
Total dissolved solids (mg/L)	TDS	DS	76.28^{a}	55.24^{a}	249.63^{a}	493.75^{a}	100.23^{a}	53.61^{a}	94.56^{a}	102.69^{a}
		RS	68.53^{a}	102.1^{a}	346.5^{a}	459.5^{a}	92.58^{a}	111.8^{a}	128.58^{a}	86.89^{a}
Nitrates (mg/L)	Nitra	DS	10.45^{a}	15.5^{a}	4.33^{a}	42.13^{bc}	45.38^{bc}	16.25^{a}	17.18^{a}	13.09^{a}
		RS	6.78^{a}	12.63^{a}	4.50^{a}	53.23^{bc}	37.13^{bc}	5.88^{a}	3.76^{a}	6.10^{a}
Ammonium (mg/L)	Am	DS	0.35^{a}	1.61^{a}	0.86^{a}	3.14^{b}	0.31^{ac}	0.49^{ab}	0.58^{ab}	0.65^{a}
		RS	2.27^{a}	2.63^{a}	0.38^{a}	3.48^{b}	0.42^{ac}	0.38^{ab}	0.44^{ab}	0.30^{b}
Phosphate (mg/L)	Phos	DS	0.24^{a}	0.42^{a}	0.97^{a}	1.98^{b}	1.35^{ac}	0.35^{a}	0.43^{a}	0.41^{a}
		RS	1.05^{a}	0.66^{a}	0.64^{a}	1.47^{b}	1.08^{ac}	0.37^{a}	0.83^{a}	2.22^{a}

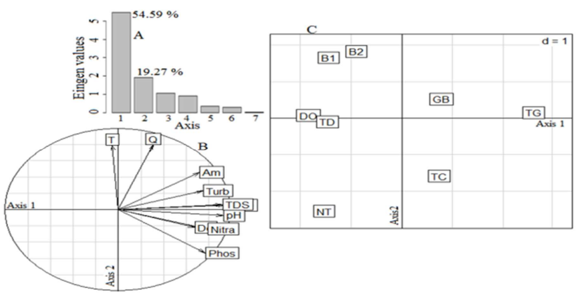

Fig. 2. Ordination diagram of sampling periods by Principal Component Analysis (PCA), considering physical and chemical variables of rivers on three mining localities. A = histogram of eigenvalues; B = correlation circle; C = factorial map; T = temperature, Turb = Turbidity, CND = Conductivity, Q = Flow of water, TDS = Total dissolved solids, Do = Dissolved oxygen, pH = Potential hydrogen, Nitra = Nitrate; Phos = Phosphate;, Am = Ammonium, B1, B2, GB, TG, TC, DO, TD and NT = Sampling stations.

Therefore, Axis 2 associated positively with temperature (T) and water flow (Q). Axis 1 makes a clear distinction between sampling stations (Fig. 2C). Stations from gold mining such as Gbloh (GB), Tributary Gbloh (TG) and Tchindégri (TC) were located on positive part of diagram with higher conductivity, turbidity, pH, total dissolved solids, ammonium, phosphate and nitrate. This group was opposed to stations Bou 1 (B1) and Bou 2 (B2) from diamond mining and those of manganese mining (Dougodou (DO), Tributary Dougodou (TD) and N'têko (NT)). Sampling stations from diamond mining area were influenced by high values of water flow and temperature.

The Hierarchical Cluster Analysis (HCA) reveals three main groups of sampling stations (I, II and III) (Fig. 3). Group I composed of Gbloh (GB) and Tchindégri (TC) from gold mining area. Group II is formed by tributary Gbloh (TG) and the last group (III) is constitued by sampling stations (DO, TD, NT, B1 and B2) from diamond and manganese mining areas.

Periphytic community

Two hundred and twenty five (225) taxa belonging to seven (7) phyla were recorded. Regarding algal groups, green algae (Chlorophyta) were most diverse (69 taxa) followed by Euglenophyta, Bacillariophyta (diatoms) and Cyanobacteria, with respectively 60, 54 and 44 taxa. Other groups had four (9) taxa, two (2) for Dinophyta, three (3) for Ocrophyta and four (4) for Rhodophyta. Manganese mining area recorded highest diversity with 216 taxa, followed by diamond mining area with 202 taxa. Gold mining area recorded lowest diversity with 192 taxa.

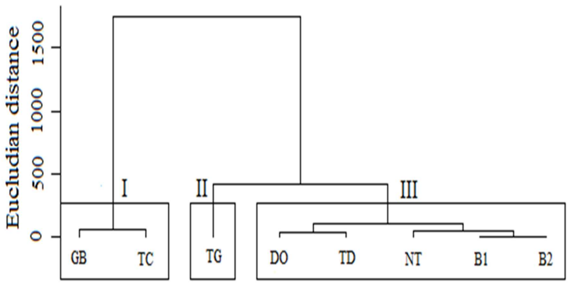

Fig. 3. Hierarchical classification of sampling stations based on physico-chemical parameters measured : I, II and III : constituted groups

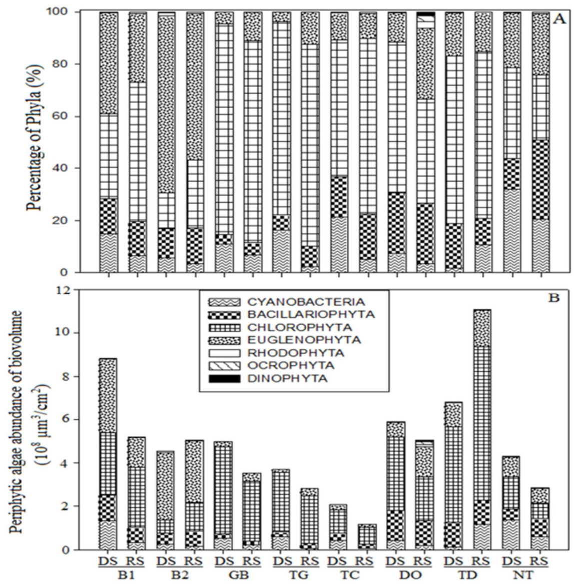

Fig. 4. Seasonality of périphytic algae biovolume at sampling stations (B) and phyla contibution (A). B1, B2, GB, TG, TC, DO, TD and NT : Sampling stations, DS : Dry season, RS : Rainy season

Stations with highest periphytic biovolume (1.11x10⁹ $\mu m^3/cm^2$) was Tributary Dougodou from manganese mining area at rainy season. It followed by Bou 1 (8.84x10⁸ $\mu m^3/cm^2$) from diamond mining area at dry season. The lowest biovolume (1.12×10^8 $\mu m^3/cm^2$) was found at Tchindégri (gold mining area) at rainy season (Fig. 4B). With regard to the contribution of the phyla to the biovolume (Fig. 4A), Chlorophyta was the most preponderant with a contribution ranging from 13.61 % at Bou 2 (diamond mining area) during dry season to 80.71 % Gbloh (gold mining area) at dry season. Second most abundant periphytic groups was Euglenophyta ranging from 3.75 % Tributary Gbloh (gold mining) to 68.04 % Bou 2 (diamond mining) during dry season. The contribution of other groups didn't exceed 30 % except for Bacillariophyta at N'têko (30.39 %) at manganese mining during the rainy season.

Variation of Shannon-Weiner's diversity and Equitability index

The spatial and seasonal variation of Shannon-Weiner index at sampling stations from three mining areas was illustrated by Fig. 5. The values of the Shannon-Weiner index varied from 0.51 at Gbloh station (gold mining area) during rainy season to 3.28 in dry season at Bou 1 (diamond mining area). The lowest values were recorded at sampling stations of gold mining area. At diamond mining area, this index varied between 1.79 and 3.28 at Bou 1 during dry season. In gold mining area, Shannon-Weiner index fluctuated from 0.51 (rainy season) to 2.64 (dry season) at Gbloh. As for manganese mining area, the index varied from 1.43 (rainy season) to 2.98 (dry season) at Tributary Dougodou.

The Shannon-Weiner index values recorded at diamond, gold and manganese mining's stations had not significant variations (Diamond mining area: Mann-Whitney test, $p > 0.05$; Gold and manganese areas: Kruskal-Wallis test, $p > 0.05$). The same observation was made seasonally between the two climatic seasons (dry and rainy) within a same station (Mann-Whitney test, $p > 0.05$).

Equitability values fluctuated from 0.16 at Gbloh (gold mining) to 0.58 at Bou 1 (diamond mining) at rainy and dry seasons respectively (Fig. 6).

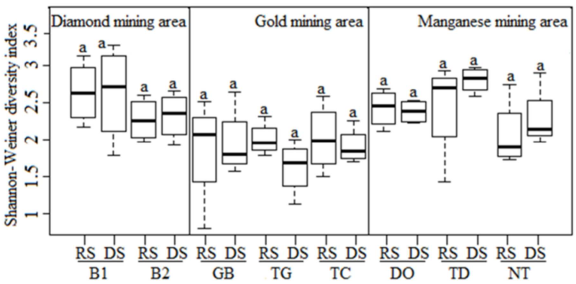

Fig. 5. Spatial and seasonal variation of Shannon-Weiner index. B1, B2, GB, TG, TC, DO, TD and NT : Sampling stations. DS : Dry Season, RS : Rainy Season. Boxplots with a letter (a) in common do not differ significantly between a locality from one station to another and from one season to another in the same station (Diamond mining area : Mann-Whitney test; $p > 0.05$; Gold and manganese mining areas : Kruskal-Wallis, $p > 0.05$).

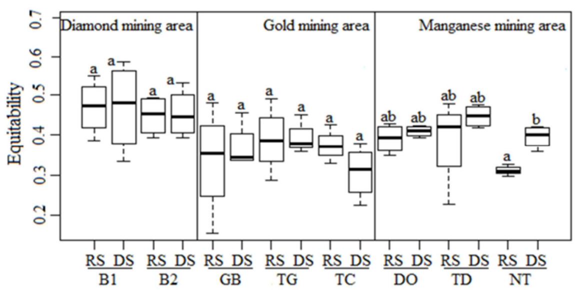

Fig. 6. Spatial and seasonal variation of Equitability index. B1, B2, GB, TG, TC, DO, TD and NT : sampling stations, DS : Dry Season, RS : Rainy Season Boxplots with a letter (a) in common do not differ significantly between a locality from one station to another (Diamond mining area : Mann-Whitney test; $p > 0.05$; Gold and manganese mining areas : Kruskal-Wallis, $p > 0.05$). Boxplots with letters in common within the same station do not differ significantly from one season to another (Mann-Whitney test, $p > 0.05$).

Equitability varied in diamond mining area from 0.33 to 0.58 at Bou 1 during dry season. In gold mining area, this index ranged between 0.16 and 0.49 in rainy season at Gbloh and Tributary Gbloh respectively. In manganese mining area, the lowest (0.22) and highest (0.47) values were recorded at Tributary Dougodou in rainy season. There is no significantly variation between stations of diamond mining area (Mann-Whitney test, $p > 0.05$), gold mining area and manganese mining area (Kruskal-Wallis test, $p > 0.05$). There is significantly difference between season at N'têko (manganese mining area) (Mann-Whitney test; $p < 0.05$).

Palmer's algal pollution index

The Table 3 showed the degre of Palmer's algal pollution index from mining areas. The total score for gold mining was greater than the two others mining areas. In gold mining, the score indicated a high organic pollution at Gbloh and tributary Gbloh. Considering the entire water parameters study and pollution index, it was clearly shown that the Tributary Gbloh (TG) sampling station was highly polluted than Gbloh and Tchindegri.

In the diamond mining area, station Bou 2 had the highest Palmer pollution index value estimated at 23. This confirms a very high organic pollution at this station. The Palmer pollution index values for manganese mining area were the lowest, ranging from 10 (N'têko) to 20 (Tributary Dougodou).

The correlations between the Palmer pollution indexes with the different abiotics parameters from mining areas are shown in Table 4 and Figs 7, 8 and 9. In diamond mining area, nitrates were significantly and negatively correlated ($p < 0.05$) with the Palmer pollution index. In gold mining area, pH was significantly and positively correlated with the Palmer pollution index. The other abiotic parameters in these mining areas were not significantly correlated ($p > 0.05$) with the Palmer pollution index. For manganese mining area, there was no significant correlation ($p > 0.05$) between the abiotics parameters and Palmer pollution index.

Similarity

Clustering (Fig. 10A), together with ordination analysis (nMDS) performed on a Bray-Curtis similarity matrix (Figure 10B), organised the periphytic algae biovolume samples in two distinct groups according to axis 1 (Fig. 10B). The first group concerned samples from diamond mining (B1 and B2).

Table 3. Palmer's algal pollution index values in sampling stations

Algae genera	Index value	Diamond mining area (Tortiya)		Gold mining area (Hiré)			Manganese mining area (Lauzoua)		
		B1	B2	GB	TG	TC	DO	TD	NT
Anacystis (*Microcystis*)	1	-	-	-	-	-	-	-	-
Oscillatoria	4	-	4	-	4	4	-	4	-
Phormidium	1	-	-	1	1	1		1	1
Chlamydomonas	4	-	-	-	-	-	-	-	-
Pandorina	1	-	-	-	1	-	1	1	-
Scenedesmus	4	4	4	4	4	4	-	4	4
Micratinium	1	-	-	1	1	-	1	-	-
Ankistrodesmus	2	-	-	2	2	2	-	2	-
Chlorella	3	-	-	-	-	-	-	-	-
Closterium	1	1	1	1	1	1	-	1	1
Stigeoclonium	2	-	2	2	2	2	-	-	2
Cyclotella	1	-	-	1	-	-	-	-	-
Melosira	1	-	-	-	-	-	-	-	-
Gomphonema	1	-	1	1	1	1	1	-	1
Navicula	3	3	3	-	3	3	3	3	-
Nitzschia	3	-	-	3	3	-	3	3	-
Synedra	2	-	-	-	-	-	-	-	-
Euglena	5	5	5	5	5	5	5	-	-
Phacus	2	2	2	2	2	2	-	-	-
Lepocinlis	1	-	1	1	1	1	1	1	1
Total		15	23	24	31	26	14	20	10
Total score from each mining area		23		32			29		

- : Absence of genus

Table 4. Summary of the correlations of the Palmer pollution index (IP) with the abiotics parameters of areas mining (r : correlation coefficient, p : probability, $p > 0.05$: no significant correlation and $p < 0.05$: significant correlation).

Mining areas	Abiotics prarmeters	r	p	Equation
Diamond mining area (TORTIYA)	Temperature	-0,12	0,63	IP = 26,3457 - 0,2113x
	Conductivity	0,12	0,64	IP = 19,2884 + 0,0065x
	pH	0,11	0,67	IP = 9,6181 + 1,5512x
	Dissolved oxygen	0,21	0,42	IP = 18,5748 + 0,3147x
	Turbidity	0,027	0,91	IP = 20,1518 + 0,0015x
	Total dissolved solids	0,06	0,81	IP = 19,7213 + 0,007x
	Water flow	-0,19	0,48	IP = 22,7183 - 3,4734x
	Nitrates	-0,49	0,048	IP = 22,1441 - 0,1671x
	Ammonium	-0,12	0,64	IP = 20,6686 - 0,2443x
	Phosphate	-0,44	-0,08	IP = 21,4384 - 2,0045x
Gold mining area (HIRE)	Temperature	-0,16	0,45	IP = 33,1663-0,5184*x
	Conductivity	0,3	0,14	IP = 17,4423+0,0025*x
	pH	0,47	0,01	IP = -9,6536+4,0446*x
	Dissolved oxygen	0,0092	0,96	IP = 19,1142+0,0177*x
	Turbidity	-0,16	0,43	IP = 19,9633-0,0056*x
	Total dissolved solids	0,09	0,65	IP = 18,5822+0,0023*x
	Water flow	0,37	0,07	IP = 13,4749+9,2772*x
	Nitrates	0,12	0,56	IP = 18,4405+0,026*x
	Ammonium	0,16	0,43	IP = 18,5246+0,5069*x
	Phosphate	-0,05	0,80	IP = 19,7154-0,3732*x
Manganese mining area (LAUZOUA)	Temperature	0,24	0,25	IP = -0,3178+0,8352*x
	Conductivity	0,24	0,25	IP = 18,659+0,0164*x
	pH	0,02	0,93	IP = 20,4406+0,2189*x
	Dissolved oxygen	0,21	0,31	IP = 19,4084+0,537*x
	Turbidity	0,22	0,30	IP = 20,9764+0,0262*x
	Total dissolved solids	0,29	0,16	IP = 18,4218+0,0367*x
	Water flow	0,66	0,0004	IP = 17,7707+13,259*x
	Nitrates	-0,18	0,4	IP = 22,9392-0,0945*x
	Ammonium	-0,01	0,96	IP = 22,0736-0,2427*x
	Phosphate	-0,17	0,42	IP = 22,5568-0,775*x

Table 5. Mean dissimilarity (M.D) and percentage specific contribution of the main periphytic algae taxa (R-statistic and p-value) from the SIMPER similarity analysis. See text about paragraph 4. Determinism of periphytic algae settlement for species acronyms, M.D: Mean (dis) similarity, B1, B2, GB, TG, TC, DO, TD, NT: sampling stations

Locality	Stations comparaison	M. D	ANOSIM R	p	SIMPER Main taxa (Contribution; 2 %)
Diamond mining area (Tortiya)	B1 & B2	62.32	0.037	0.214	Spsp1 (12.92%), Epol (11.34%), Apla (5.93%), Phsp (5.34%), Plef (4.89%), Cmon (3.15%), Lesp (2.73%), Uacu (2.60 %), Pcyl (2.12), Pdup (2.01) and Lacu (2.00)
Gold mining area (Hiré)	GB & TG	49.58	0.109	0.116	Stsp2 (20.27%), Spsp2 (19.29%), Spsp1 (9.67%), Apla (6.64%), Cerh (5.56%), Acap (5.35%) and Pcyl (4.96%)
	GB & TC	74.04	0.430	0.0004	Spsp2 (22.87%), Spsp1 (15.75%), Pcyl (12.73%), Cerh (11.01%), Acap (5.27%), Uacu (4.76%), Apla (3.32%), Epol (3.05%), Oesp1 (3.09%)
	TG & TC	65.36	0.462	0.004	Stsp2 (28.21%), Pcyl (13.67%), Spsp1 (7.55%), Cerh (7.29%), Spsp2 (6.42%), Uacu (5.88%), Cmon (4.12%), Apla (3.68%) and Pdup (2.94%)
Manganese mining area (Lauzoua)	DO & TD	27.34	0.037	0.247	Spsp2 (24.99%), Cerh (13.47%), Pcyl (6.35%), Apla (5.71%), Spsp1 (4.41%), Epol (4.32%), Frsp (3.75%) and Oesp2 (2.98%),
	DO & NT	59.68	0.260	0.002	Spsp2 (29.79%), Pcyl (21.42%), Cerh (10.50%) Apla (10.39%), Spsp1 (5.43%), Frsp (3.26%), Uuln (2.68%) and Phsp (2.14%)
	TD & NT	52.44	0.037	0.247	Pcyl (21.67%), Cerh (20.97%), Apla (9.09%), Spsp2 (6.59%), Epol (3.35%), Oesp2 (3.26%) and Spsp1 (2.67%),

Table 6. Information expressed by axis of canonical correspondence analysis

AXIS	I	II	III	IV
Eigenvalues	0.509	0.298	0.183	0.01
Percentage of variances	50.9	29.8	18.3	1
Cumulative percentage	50.9	80.7	99	100

The second group included samples from gold mining (GB, TG and TC) and manganese mining (DO, TD and NT). The differences between these groups were confirmed by ANOSIM analysis ($R = 0.45$; $p < 0.05$). The species responsible for the discrimination between these groups were identified using results of the SIMPER analysis (Table 5).

The nMDS biplot (Stress = 0.01) showed that the Bou 1 and Bou 2 stations were not clearly differentiated. The ANOSIM results indicated that there was no significant change in the composition of the algal periphytic community between stations in diamond mining (global R ANOSIM = 0.037; p = 0.214; Table 5). According to the SIMPER analysis, the main taxa responsible for the homogeneity and similarity between Bou 1 and Bou 2 stations from diamond mining were characterised by the predominance of the biovolume of : 2 taxa of Cyanobacteria (*Aphanocapsa planctonica* (Apla) and *Phormidium* sp. (Phsp)) ; 4 taxa of Euglenophyta (*Phacus lefevrei* (Plef), *Euglena polymorpha* (Epol), *Lepocinclis* sp. (Lesp) and *Lepocinclis acus* (Lacu)) ; 4 taxa of Chlorophyta (*Spirogyra* sp.1 (Spsp1), *Closterium monoliferum* (Cmon), *Pleurotaenium cylindricum* (Pcyl) and *Pediastrum duplex* (Pdup)) and 1 taxa of Bacillariophyta (*Ulnaria acus* (Uacu)) (Table 5).

In gold mining area, the nMDS plots (stress = 0.04) and ANOSIM analyses (Table 5) showed that the periphytic community compositions were not clearly separated and significantly different between Gbloh and Tributary Gbloh stations (ANOSIM global R = 0.109; p = 0.116). The species responsible for this homogeneity according to SIMPER analyses (Table 5) were characterised by the preponderance of the biovolume of one Cyanobacteria taxa (*Aphanocapsa planctonica* (Apla)), six (6) Chlorophyta taxa (*Actinotaenium capax* (Acap), *Spirogyra* sp.1 (Spsp1), *Spirogyra* sp.2 (Spsp2), *Closterium ehrenbergii* (Cehr), *Pleurotaenium cylindricum* (Pcyl)) and *Stigeoclonium* sp.2 (Stsp2).

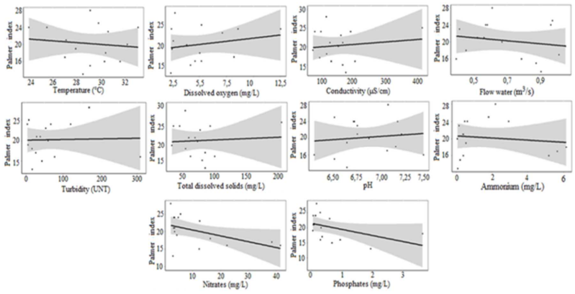

Fig. 7. Linear regression lines for abiotics parameters and Palmer pollution index in diamond mining area

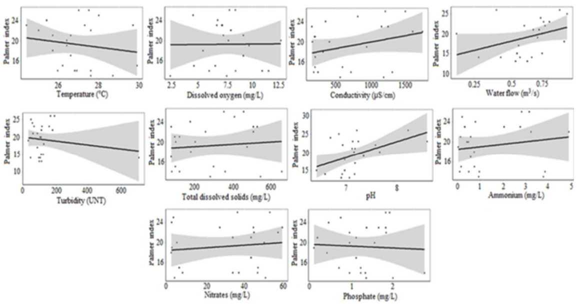

Fig. 8. Linear regression lines for abiotics parameters and Palmer pollution index in gold mining area

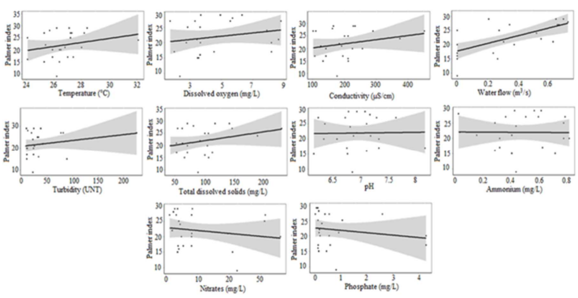

Fig. 9. Linear regression lines for abiotics parameters and Palmer pollution index in manganese mining area

In contrast, the Gbloh and Tchindégri stations were well separated (global R ANOSIM = 0.430; p = 0.0004) according to SIMPER analyses (Table 5). The species whose contributed for this separation were *Aphanocapsa planctonica* (Apla) of Cyanobacteria, *Spirogyra* sp.2 (Spsp2), *Spirogyra* sp.1 (Spsp1), *Pleurotaenium cylindricum* (Pcyl), *Closterium ehrenbergii* (Cehr), *Actinotaenium capax* (Acap) and *Oedogonium* sp.1 (Oesp1) of Chlorophyta, *Ulnaria acus* (Uacu) of Bacillariophyta and *Euglena polymorpha* (Epol) of Euglenophyta.

The Tributary Gbloh and Tchindegri stations were also separated (global R ANOSIM = 0.462; p = 0.004). The species with the highest biovolume according to SIMPER analyses (Table 5) between these two stations were *Stigeoclonium* sp.2 (Stsp2), *Pleurotaenium cylindricum* (Pcyl), *Spirogyra* sp.1 (Spsp1), *Closterium ehrenbergii* (Cehr), *Spirogyra* sp.2 (Spsp2), *Closterium monoliferum* (Cmon) and *Pediastrum duplex* (Pdup) of Chlorophyta, *Ulnaria acus* (Uacu) of Bacillariophyta and *Aphanocapsa planctonica* (Apla) of Cyanobacteria.

Concerning manganese mining, clustering and ordination analysis (nMDS) performed on a Bray-Curtis similarity matrix organised the samples into two distinct groups. The Dougodou and Tributary Dougodou stations were grouped in the nMDS biplot (Stress = 0.02). These two sampling stations showed a low value of R (0.037), which implied a low similarity between their taxonomic compositions. In terms of biovolume contribution to periphytic community similarity, the most important species were *Spirogyra* sp.2 (Spsp2), *Closterium erhenbergii* (Cerh), *Pleurotaenium cylindricum* (Pcyl), *Spirogyra* sp.1 (Spsp.1) and *Oedogonium* sp.2 (Oesp.2) of Chlorophyta. One taxa (*Euglena polymorpha* (Epol)) came from the phylum Euglenophyta. *Aphanocapsa planctonica* (Apla) and *Fragilaria* sp. (Frsp) were from Cyanobacteria and Bacillariophyta respectively.

The biovolume contribution of periphytic taxa showed a significant difference between the Dougodou and N'têko stations (global R ANOSIM = 0.260, p = 0.002). Thus, this situation was mainly characterised by *Spirogyra* sp.2 (Spsp2), *Pleurotaenium cylindricum* (Pcyl), *Closterium erhenbergii* (Cerh), *Aphanocapsa planctonica* (Apla), *Spirogyra* sp.1 (Spsp1), *Fragilaria* sp. (Frsp), *Ulnaria* *ulna* (Uuln) and *Phormidium* sp. (Phsp). ANOSIM analyses (Table 5) revealed no significant difference in periphytic communities between the stations Tributary Dougodou and N'têko (global R ANOSIM = 0.037; p = 0.247). The taxa *Pleurotaenium cylindricum* (Pcyl), *Closterium ehrenbergii* (Cerh), *Oedogonium* sp.2 (Oesp2) and *Spirogyra* sp.1 (Spsp1), *Spirogyra* sp.2 (Spsp2) of Chlorophyta, *Aphanocapsa planctonica* (Apla) and *Euglena ploymorpha* (Epol) respectively of Cyanobacteria and Euglenophyta characterised this weak similarity.

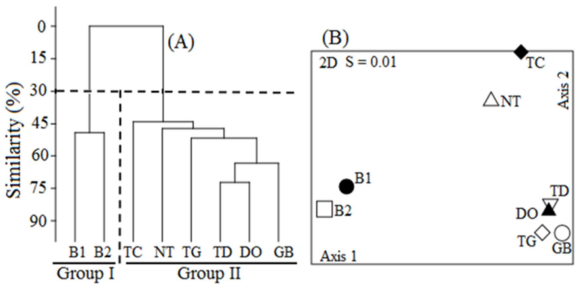

Fig. 10. Clustering based on a similarity matrix of biovolume of periphytic Bray Curtis taxa (A) and Ordination analysis (nMDS) performed on the basis of a similarity matrix of biovolume of periphytic Bray-Curtis taxa (B). B1, B2, GB, TG, TC, DO, TD and NT : Sampling stations

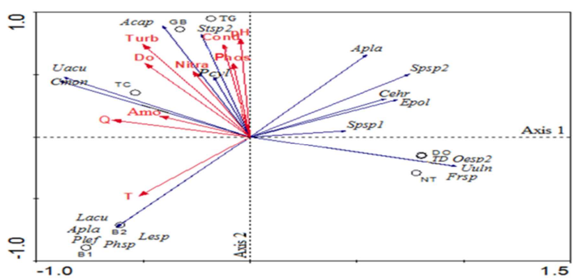

Fig. 11. Canonical Correspondence Analysis based on specific biovolume of periphytic algae taxa in relation with environmental factors. B1, B2, GB, TG, TC, DO, TD and NT : sampling stations

Determinism of periphytic algae settlement

The canonical redundancy analysis carried out from periphytic algae biovolume with relative abundance greater than 2 % in sampling stations and abiotic parameters provides a synthetic visualization of the information summarized on the first two (1 and 2) axis. The Monte-Carlo permutation test indicates that the result of this analysis was significant (p < 0.05).

The table 6 showed the variances of the first four axes of the total information from canonical redundancy analysis at each locality. The first two axis expressing 80.7 % of the total variability (50.9% for axis 1 and 29.8 % for axis 2). Axis 1 was positively correlated with biovolume of *Ulnaria ulna* (Uuln), *Fragilaria* sp. (Frsp), *Oedogonium* sp.2 (Oesp2), *Spirogyra* sp.1 (Spsp1), *Euglena polymorpha* (Epol) and *Closterium ehrenbergii* (Cehr) at sampling stations Dougodou (DO), Tributary Dougodou (TD) and N'têko (NT) from manganese mining area. These taxa were not influenced by any environmental variable. The same axis was negatively correlated with ammonium (Amo) and water flow (Q) which influenced the biovolume of *Ulnaria acus* (Uacu) and *Closterium monoliferum* (Cmon) at Tchindegri (TC) sampling station from gold mining area. In relation to axis 2, it was positively explained by pH, conductivity (Cond), phosphate (Phos), nitrates (Nitra), Turbidity (Turb) and dissolved oxygen (Do) at Gbloh (GB) and tributary Gbloh (TG) from gold mining area. These parameters influenced the biovolume of *Pleurotaenium cylindricum* (Pcyl), *Stigeoclonium* sp.2 (Stsp2) and *Actinotaenium capax* (Acap). The axis 2 was negatively correlated with temperature (T) which influenced the biovolume of *Phacus lefevrei* (Plef), *Phacus* sp. (Phsp), *Lepocinclis acus* (Lacu), *Lepocinclis* sp. (Lesp) and *Aphanocapsa planctonica* (Apla) at sampling stations (B1 and B2) from diamond mining area (Fig. 11).

Discussion

The results of abiotic parameters indicate high temperature values in the diamond mining area (Tortiya) were recorded. This observation is thought to be related to its geographical position (arid zone with strong sunlight) and the absence of canopy at sampling stations from diamond mining area. These two effects combined would justify these high temperature values in this locality (Yoboue, 2017).

High values of turbidity, conductivity and dissolved solids were recorded in gold mining area (Hiré). This situation could be related to the artisanal and industrial gold mining activities in the vicinity of the sampling stations in this area. According to Edopkpayi *et al.* (2016), gold mining activities contribute to high levels of electrical conductivity in the rivers. Pietroń *et al.* (2017) and Martinez *et al.* (2018) stated that the impacts of gold mining lead to increased sediment transport, suspended particles and turbidity. In addition, nutrients (nitrates, ammonium and phosphate) concentration have considerably elevated at gold mining area. In fact, traditional gold panning was increasingly intense in the gold mining area with a larger workforce. During gold mining, the gold panners generate large quantities of waste in the watercourses. These actions reduced the inflow of light into the ecosystem and affected the energy flow of the system, resulting in reduced productivity levels (Vázquez and Favila, 2011). The result of ACP confirms the influence of abiotic parameters on the Gold mining area.

Indeed, at the level of taxonomic richness (225 taxa), in terms of taxonomic diversity, manganese mining area had high values while gold mining area recorded lowest diversity.

Diamond and manganese mining area presented high specific richness and algal biovolume. The gold mining area appeared to be relatively poor in taxa (196 taxa) and had a low biovolume. The low taxonomic richness observed in gold mining area could be attributed to mining activities in this area, which generate large amounts of sediment, thus disturbing the environment and reducing algal diversity. The floristic composition showed a dominance of Chlorophyta. Salla (2015) and Adeniyi and Akinwole (2017) have made similar observations respectively in two rivers (Mé and Boubo) of Côte d'Ivoire and in river of Edo state in Nigeria. The predominance of Chlorophyta would be due to an environment much more disturbed by pollution. Indeed, the genera *Cosmarium*, *Closterium* and *Scenedesmus*, dominating in numbers of species testified to polluted environments rich in organic substances coming from the immediate environment (Reynolds and Melo, 2000).

Shannon-Wiener and equitability indices are a widely used tool for measuring biodiversity and ecological health of a habitat. Therefore, it is commonly used to assess water quality (Chankaew *et al.*, 2023). In this study, the lowest values of Shannon-Weiner index were recorded in gold mining area. According to Spellerberg *et al.* (2003) when the values of the Shannon-Wiener index of a habitat were low, this habitat presents a moderate level of pollution. In view of the above, gold mining area is therefore the most disturbed compared to other two mining area. These low values of the Shannon-Wiener diversity index in gold mining area indicated an environment that was not very conducive to algal development and indicated that the water bodies were relatively unfavourable environments for a large number of taxa. This result is comforted by those of the algal pollution index of Palmer, which indicates a probable or high organic pollution in all rivers from gold mining areaAlgae, being a primary inhabitant of water, plays a significant role in the ecology of these water bodies. Algal communities are dominated by *Chrooccoccus, Ankistrodesmus, Dictyosphaerium, Pediastrum, Scenedesmus, Trachelomonas, Melosira* and *Nitzschia*. Their presence is an indication of organic pollution of the water as established by Palmer (1969) and Veenashree *et al.* (2022). The genus, *Scenedesmus* is present in all the sites, its occurrence in polluted water, especially in eutrophicated water, is established by Tripathi *et al.* (1987). Palmer (1969) also gave a high ranking for this genus. All the sites showed high level of organic pollution according to the Palmer's index. This is substantiated by the physico-chemical analysis of the water, which showed moderate levels of pollution. The study concludes that all water bodies in the study sites are in potential danger of being polluted by human activities. The three mining activities (gold, diamond and manganiferous) degrade the quality of the rivers, especially that of the products from the gold mining. In this study, we compared the species composition and distribution of periphytic algae communities among three rivers systems. Differences appeared in the variations of the biovolume of the taxa.

Conclusion

The investigations carried out during this study on abiotic parameters and periphytic algae communities from rivers about three mining areas made it possible to draw up a report on composition and structure of periphytic populations. The temperature of water at sampling stations and flow of water recorded were higher at diamond mining area (Tortiya). In sampling stations from gold mining area (Hiré), water was much more turbid with high values of conductivity and total dissolved solids. From a taxonomic point of view, a total of 225 taxa were recorded during this study. Manganese mining area recorded the highest taxonomic richness while the lowest was obtained in the gold mining. The best represented algal groups in the stands was Chlorophyta. Gold mining area was found to have the lowest taxonomic richness; biovolume and diversity indices. According to Palmer's index, gold mining area presented a highest values. It would therefore be the environment most disturbed by gold mining activity that takes place. Manganese and diamond mining at Lauzoua and Tortiya respectively have a lesser effect on the organisation of the periphytic algal community. The study concludes that the traditional water bodies in the study sites are in potential danger of being polluted by human activity.

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