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Microalgae removal from Ghrib Dam (Ain Defla, Algeria) water by electroflotation using stainless steel electrodes

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ABSTRACT

This study investigates the microalgae removal from Ghrib Dam water by electroflotation (EF) using stainless steel electrodes. The results obtained show that EF is excellent in microalgae removal (~100%). The effects of parameters such as: current density (i), initial pH and distance between electrodes (d) are examined. The optimal conditions are: $i = 170\ A\ m^{-2}$ and $d = 1$ cm during 15 min at pH 7.8. Future research must focus on microalgae lysis, toxin release and degradation due to EF treatment. Precautions must be taken such as reducing the applied voltage, increasing the residence time in the electrochemical device and adding a powdered activated carbon adsorption stage.

Keywords: Electroflotation (EF); Microalgae; Surface water; Disinfection by-products formation (DBPs); Stainless steel electrodes (SSEs); Ghrib Dam (GD)

1. Introduction

A significant presence of microalgae and cyanobacteria in aquatic systems remains a major problem in the treatment of drinking water [1–7]. Under certain conditions, especially for the rich waters in nutrients and exposed to sunlight, algae can grow to reach high concentrations, a phenomenon referred to as *algal bloom* [8]. The proliferation of microscopic algae and metabolites they secrete may cause disturbances on streams of water treatment and thus degrade the quality of water intended for human consumption. In particular, the compounds responsible for taste and odour, and algal toxins are likely to be found in the treated water as the conventional systems (i.e. coagulation/flocculation, sedimentation, sand filtration and post-chlorination) of drinking water treatment are not necessarily designed to retain the dissolved compounds [9].

The treatment used must be suitable for the removal of these micro-organisms [10]. However, research on non-conventional methods should be made to better eliminate microalgae. Electrochemical processes, such as electroflotation (EF), are experiencing a growing interest over the past three decades as they have been found effective in the removal of several pollutants such as mineral, organic, microbial and algal types [6,11–17]. EF uses electrolysis only to produce gas bubbles which uplift the flocculated algae to the surface. The electrodes are placed horizontally, covering the bottom of the flotation tank. This geometric configuration makes the EF technique similar to dissolved air flotation [18]. The application of an

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electric field produces electrochemical reactions which affect the performance of the EF process [19]:

At the cathode:

$$2H_2O_{(l)} + 2e^- \rightarrow H_{2(g)} + 2OH^-_{(aq)} \quad E_0 = -0.83\,V \quad (1)$$

$$2H_3O^+_{(aq)} + 2e^- \rightarrow 2H_2O_{(l)} + H_{2(g)} \quad E_0 = 0\,V \quad (2)$$

E_0 is the standard electrode potential at 298°K.

At the anode:

$$2H_2O_{(l)} \rightarrow O_{2(g)} + 4H^+_{(aq)} + 4e^- \quad E_0 = 1.23\,V \quad (3)$$

The objective of this study is to evaluate the efficacy of EF process for the elimination of microalgae in the Ghrib Dam (GD) waters (Ain Defla). The parameters influencing the efficiency of the process are optimised. The evaluation of this process focuses on the reduction of the number of microalgae that are found in water before and after treatment.

2. Experimental details

2.1. Experimental procedure

EF tests have been realised using an equipment which is composed of two stainless steel electrodes (SSEs). The electrodes are of the same dimensions (4.5 × 20 cm) and plunged in a Plexiglas tank with 0.9 L as volume (21 × 5.5 × 8 cm). For each electrode, the immerged surface is 90 cm^2 (4.5 × 20 cm). Since the electrodes are totally immerged in the reactor, the active surface is $S_a = 2 \times 90 = 180\,cm^2$. The gap between the electrodes is fixed at a certain distance. The electrodes are connected to a direct current power supply (Enyl1 Elektrolyser) with 15 V as maximal voltage and 10 A as maximal intensity. Applied voltage U (V) and current intensity I (A) are measured by voltammeter and ammeter connected in parallel and in series, respectively.

Before EC tests, in order to avoid any interference, SSEs are prepared as follows: (1) rinse with distilled water and polish using abrasive paper, (2) clean in chlorhydric acid solution (HCl at 20%) during 10 min, and (4) rinse with distilled water. All used chemicals are of analytical grade.

2.2. Analytical techniques

In this research, several parameters are studied to get the optimum conditions for microalgae removal such as the pH of the medium, the applied voltage U (V), EF time (t_{EF}) and the inter-electrode distance d. In the Plexiglas container filled with $V = 600$ mL of surface water and after the measurement of conductivity and pH, the cleaned electrodes (active surface area of 46.75 cm^2) are plunged. EF treatment is performed on an installation mounted in the laboratory. It is composed of two SSEs which are perforated and laid horizontally. Since the electrodes are perforated, the real active surface area would be $S_{ra} = 46.75\,cm^2 \times 2 = 93.5\,cm^2$ instead of $S_a = 180\,cm^2$. The anode is connected to the positive pole and the cathode to the negative pole of the power supply. Fig. 1 shows the diagram of the experimental set-up of the EF.

2.3. Sampling and algological analysis

After settling and using a pipette, 25 mL of the solution is taken carefully for necessary analyses. EF changes the initial pH of the solution and its conductivity, while the measure is necessary before and after treatment to really see the EF effect on pH and conductivity. The samples are placed in the Utermohl room (chamber). A drop of iodine (lugol) is added to fix the microalgae and a settling time of 24 h will be given. The sediment is collected and placed on the inverted microscope slide (at the National Agency for Water Resources (ANRH) Laboratories). On these samples, the species were identified and counted under an inverted microscope following the Utermohl method [20] modified by Legendre and Watt [21]. The algae number per mL is calculated by following Eq. (4):

$$N\left(\frac{\text{algae}}{\text{mL}}\right) = \frac{\text{Number of organism counted} \times \text{Number of fields} \times 1,000}{\text{Number of fields surveyed} \times \text{Concentrated volume}} \quad (4)$$

The calculation of removal efficiency of microalgae is performed using Eq. (5):

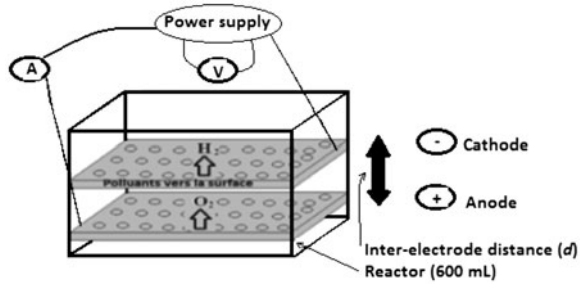

Fig. 1. Diagram of the EF setup.

$$R(\%) = \frac{c_i - c_f}{c_i} \times 100 \quad (5)$$

where c_i and c_f are the initial and final concentrations of microalgae (before and after treatment), respectively. All the chemical analyses are performed by the ANRH Laboratory following the standard methods [22].

3. Results and discussion

3.1. Characteristics of GD water

3.1.1. Physicochemical parameters

Before studying the EF effectiveness on the microalgae elimination of microalgae, a collection of water features of GD during the study period from the month of February–June is made. Physicochemical data recorded by the ANRH Laboratory are listed in Table 1. Samples were taken from the surface of GD. In addition, high concentrations of the total hardness (910 mg $CaCO_3$/L during the month of June) are due to the geological nature of the watershed of GD-containing limestone. In general, the GD water is not very good because of the sulphate concentrations, which can become a limiting factor in the productivity of the lake. Moreover, the absence of gypsum rocks and pyrite would suggest that the origin of these very high levels is mainly due to wastewater discharges. The results of these analyses clearly confirm that the GD water is alkaline, hard, sulphated, chlorinated and rich in lime. Some values such as chlorides, sulphates and calcium exceed standards which may cause a risk to consumer health (formation of kidney stones, gastrointestinal irritation, etc.) [22].

3.1.2. Algological parameters

Table 2 presents an algological analysis (identification and enumeration of microalgae) of the raw water taken from the GD surface during the month of April 2011. The most common species of microalgae are from the class of Bacillariophyceae, gender *Cyclotelle*. Others appear regularly: *Synedra* (the same class), *Scenedesmus* (*S. dimorphus* and *S. quadricauda*), *Volvox carteri*, *Tetraedron* (*T. caudatum* and *T. minimum*) and *Causmarium depressum* are from the class of *Chlorophyceae*.

3.2. Observed phenomena during EF process

During EF experiments, the observed phenomena are as follows: (1) Release of gas bubbles at the electrodes. (2) Formation and ascension of the flocs by gas bubbles formed. (3) After the flocs flotation, the solution becomes clear. (4) Raising of the temperature

Table 1
Physicochemical parameters of GD from February to August 2011

Parameters	February	March	April	May	June	July	August
Ca^{2+} (mg/L)	125	162	188	162	191	184	176
Mg^{2+} (mg/L)	100	90	87	89	105	96	91
Na^{+} (mg/L)	421	335	229	401	320	278	330
K^{+} (mg/L)	11	10	4	4	5	8	6
Cl^{-} (mg/L)	446	430	463	455	540	408	420
SO_4^{2-}(mg/L)	740	695	680	783	750	715	808
NO_3^{-} (mg/L)	2.2	2.9	2.4	4.8	2.9	2.3	7.6
pH	7.9	7.9	8.0	8.0	8.0	7.9	7.9
Conductivity (μS/cm)	3,300	3,000	2,610	3,000	3,000	2,760	3,100
Dry residue (mg/L)	2,397	2,112	1,644	2008	1,769	1,770	1905
Total hardness (mg/L as $CaCO_3$)	730	780	830	780	910	860	820
Total alkalinity (mg/L as $CaCO_3$)	120	170	110	130	110	110	90
Alkalinity (mg/L as $CaCO_3$)	0	0	0	0	0	0	0
NO_2^{-} (mg/L)	0.034	0.072	0.000	0.000	0.075	0.000	0.069
NH_4^{+} (mg/L)	0.194	0.264	0.100	0.135	0.069	0.033	0.047
$KMnO_4$ oxidability (mg/L)	6.0	7.9	6.0	7.6	7.4	6.5	7.2
Dissolved oxygen (mg/L)	10.2	9.5	5.9	6.6	6.7	9.0	6.9
Water temperature (°C)	10.0	18.0	18.0	21.0	19.0	26.0	28.0
Chemical oxygen demand (mg/L)	9.0	9.0	34.0	18.0	16.0	9.0	/
Turbidity (NTU)	4.2	2.7	/	/	/	2.7	/

Table 2
Algological analysis of GD water for April 2011 and treated water by EF at different experimental conditions

	Class	Genre	Species	Cells*
GD water (April 2011) [215 cells]	Bacillariophyceae	*Synedra*		5
	Bacillariophyceae	*Cyclotelle*	*comta*	190
	Chlorophycea	*Scenedesmus*	*dimorphus*	2
	Chlorophycea	*Scenedesmus*	*quadricauda*	6
	Chlorophycea	*Volvox*	*carteri*	5
	Chlorophycea	*Tetraedron*	*caudatum*	1
	Chlorophycea	*Causmarium*	*depressum*	3
	Chlorophycea	*Tetraedron*	*miminum*	2
	Chlorophycea	*Scenedesmus*	*ecornis*	1
E#1 GD water treated by EF at pH 7.8, $i = 29\ A/m^2$, $t_{EF} = 5$ min and $d = 2$ cm [37 cells, 82.8%]	Bacillariophyceae	*Synedra*		1
	Bacillariophyceae	*Cyclotelle*	*comta*	34
	Chlorophycea	*Scenedesmus*	*dimorphus*	1
	Chlorophycea	*Scenedesmus*	*ecornis*	1
E#2 GD water treated by EF at pH 7.8, $i = 103\ A/m^2$, $t_{EF} = 5$ min and $d = 2$ cm [15 cells, 93%]	Bacillariophyceae	*Cyclotelle*	*comta*	13
	Chlorophycea	*Tetraedron*	*miminum*	1
	Chlorophycea	*Scenedesmus*	*ecornis*	1
E#3 GD water treated by EF at pH 7.8, $i = 170\ A/m^2$, $t_{EF} = 5$ min and $d = 2$ cm [13 cells, 93.9%]	Bacillariophyceae	*Cyclotelle*	*comta*	12
	Chlorophycea	*Scenedesmus*	*ecornis*	1
E#4 GD water treated by EF at pH 7.8, $i = 29\ A/m^2$, $t_{EF} = 10$ min and $d = 2$ cm [19 cells, 91.2%]	Bacillariophyceae	*Synedra*		1
	Bacillariophyceae	*Cyclotelle*	*comta*	14
	Chlorophycea	*Scenedesmus*	*quadricauda*	3
	Chlorophycea	*Scenedesmus*	*ecornis*	1
E#5 GD water treated by EF at pH 7.8, $i = 103\ A/m^2$, $t_{EF} = 10$ min and $d = 2$ cm [19 cells, 91.2%]	Bacillariophyceae	*Synedra*		3
	Bacillariophyceae	*Cyclotelle*	*comta*	10
	Chlorophycea	*Scenedesmus*	*quadricauda*	2
	Chlorophycea	*Volvox*	*carteri*	3
	Chlorophycea	*Tetraedron*	*miminum*	1
E#6 GD water treated by EF at pH 7.8, $i = 170\ A/m^2$, $t_{EF} = 10$ min and $d = 2$ cm [17 cells, 92.1%]	Bacillariophyceae	*Cyclotelle*	*comta*	12
	Chlorophycea	*Volvox*	*carteri*	3
	Chlorophycea	*Tetraedron*	*miminum*	2
E#7 GD water treated by EF at pH 7.8, $i = 29\ A/m^2$, $t_{EF} = 15$ min and $d = 2$ cm [2 cells, 99%]	Bacillariophyceae	*Cyclotelle*	*comta*	1
	Chlorophycea	*Volvox*	*carteri*	1
E#8 GD water treated by EF at pH 7.8, $i = 29\ A/m^2$, $t_{EF} = 25$ min and $d = 2$ cm [12 cells, 94.4%]	Bacillariophyceae	*Cyclotelle*	*comta*	5
	Chlorophycea	*Scenedesmus*	*quadricauda*	2
	Chlorophycea	*Volvox*	*carteri*	4
	Chlorophycea	*Tetraedron*	*miminum*	1
E#9 GD water treated by EF at pH 7.8, $i = 103\ A/m^2$, $t_{EF} = 25$ min and $d = 2$ cm [2 cells, 99%]	Bacillariophyceae	*Cyclotelle*	*comta*	2
E#10 GD water treated by EF at pH 7.8, $i = 29\ A/m^2$, $t_{EF} = 30$ min and $d = 2$ cm [4 cells, 98.1%]	Bacillariophyceae	*Synedra*		1
	Bacillariophyceae	*Cyclotelle*	*comta*	1
	Chlorophycea	*Scenedesmus*	*dimorphus*	2

(*Continued*)

Table 2
(*Continued*)

	Class	Genre	Species	Cells*
E#11 GD water treated by EF at pH 4.0, $i = 170\ A/m^2$, $t_{EF} = 15$ min and $d = 2$ cm [3 cells, 98.6%]	Bacillariophyceae	*Synedra*		1
	Bacillariophyceae	*Cyclotelle*	*comta*	1
	Chlorophycea	*Scenedesmus*	*dimorphus*	1
E#12 GD water treated by EF at pH 4.0, $i = 103\ A/m^2$, $t_{EF} = 20$ min and $d = 2$ cm [29 cells, 86.5%]	Bacillariophyceae	*Cyclotelle*	*comta*	29
E#13 GD water treated by EF at pH 4.0, $i = 29\ A/m^2$, $t_{EF} = 25$ min and $d = 2$ cm [48 cells, 77.7%]	Bacillariophyceae	*Cyclotelle*	*comta*	48
E#14 GD water treated by EF at pH 4.0, $i = 103\ A/m^2$, $t_{EF} = 25$ min and $d = 2$ cm [19 cells, 91.2%]	Bacillariophyceae	*Cyclotelle*	*comta*	19
E#15 GD water treated by EF at pH 4.0, $i = 29\ A/m^2$, $t_{EF} = 30$ min and $d = 2$ cm [59 cells, 72.5%]	Bacillariophyceae	*Cyclotelle*	*comta*	58
	Chlorophycea	*Scenedesmus*	*ecornis*	1
E#16 GD water treated by EF at pH 4.0, $i = 103\ A/m^2$, $t_{EF} = 30$ min and $d = 2$ cm [14 cells, 93.5%]	Bacillariophyceae	*Cyclotelle*	*comta*	14
E#17 GD water treated by EF at pH 10.0, $i = 29\ A/m^2$, $t_{EF} = 5$ min and $d = 2$ cm [13 cells, 93.9%]	Bacillariophyceae	*Cyclotelle*	*comta*	13
E#18 GD water treated by EF at pH 10.0, $i = 103\ A/m^2$, $t_{EF} = 5$ min and $d = 2$ cm [10 cells, 95.3%]	Bacillariophyceae	*Cyclotelle*	*comta*	10
E#19 GD water treated by EF at pH 10.0, $i = 170\ A/m^2$, $t_{EF} = 5$ min and $d = 2$ cm [11 cells, 94.9%]	Bacillariophyceae	*Cyclotelle*	*comta*	11
E#20 GD water treated by EF at pH 10.0, $i = 29\ A/m^2$, $t_{EF} = 10$ min and $d = 2$ cm [11 cells, 94.9%]	Bacillariophyceae	*Cyclotelle*	*comta*	11
E#21 GD water treated by EF at pH 10.0, $i = 103\ A/m^2$, $t_{EF} = 10$ min and $d = 2$ cm [4 cells, 98.1%]	Bacillariophyceae	*Cyclotelle*	*comta*	4
E#22 GD water treated by EF at pH 10.0, $i = 29\ A/m^2$, $t_{EF} = 15$ min and $d = 2$ cm [4 cells, 98.1%]	Bacillariophyceae	*Cyclotelle*	*comta*	4
E#23 GD water treated by EF at pH 10.0, $i = 103\ A/m^2$, $t_{EF} = 15$ min and $d = 2$ cm [3 cells, 98.6%]	Bacillariophyceae	*Cyclotelle*	*comta*	3
E#24 GD water treated by EF at pH 10.0, $i = 103\ A/m^2$, $t_{EF} = 20$ min and $d = 2$ cm [1 cell, 99.5%]	Bacillariophyceae	*Cyclotelle*	*comta*	1
E#25 GD water treated by EF at pH 6.0, $i = 29\ A/m^2$, $t_{EF} = 10$ min and $d = 2$ cm [14 cells, 93.5%]	Bacillariophyceae	*Cyclotelle*	*comta*	14
E#26 GD water treated by EF at pH 6.0, $i = 29\ A/m^2$, $t_{EF} = 20$ min and $d = 2$ cm [14 cells, 93.5%]	Bacillariophyceae	*Cyclotelle*	*comta*	14
E#27 GD water treated by EF at pH 6.0, $i = 29\ A/m^2$, $t_{EF} = 30$ min and $d = 2$ cm [10 cells, 95.3%]	Bacillariophyceae	*Cyclotelle*	*comta*	10

(*Continued*)

Table 2
(*Continued*)

	Class	Genre	Species	Cells*
E#28 GD water treated by EF at pH 7.8, $i = 29\ A/m^2$, $t_{EF} = 5$ min and $d = 1$ cm [13 cells, 93.9%]	Bacillariophyceae	*Cyclotelle*	*comta*	13
E#29 GD water treated by EF at pH 7.8, $i = 29\ A/m^2$, $t_{EF} = 10$ min and $d = 1$ cm [10 cells, 93.5%]	Bacillariophyceae	*Cyclotelle*	*comta*	10
E#30 GD water treated by EF at pH 7.8, $i = 103\ A/m^2$, $t_{EF} = 5$ min and $d = 1$ cm [10 cells, 93.5%]	Bacillariophyceae	*Cyclotelle*	*comta*	10
E#31 GD water treated by EF at pH 7.8, $i = 103\ A/m^2$, $t_{EF} = 10$ min and $d = 1$ cm [3 cells, 98.6%]	Bacillariophyceae	*Cyclotelle*	*comta*	3

during EF processing. In EF, with SSEs, the anode produces oxygen and the cathode produces hydrogen gas, which results in the flotation of the flocs to the surface [23].

3.3. Parameters influencing EF process

The influence of some EF operating parameters such as current density i, time t_{EF}, inter-electrode distance (d) and physicochemical properties of the surface water such as pH and conductivity are examined.

3.3.1. EF time effect

EF time plays a very important role. Fig. 2 shows the evolution of the removal rate of microalgae as a function of EF time, the other parameters are kept constant: pH 7.8, $i = 29\ A/m^2$ and $d = 2$ cm. The flocs formed are trained by the gas bubbles to the solution surface to constitute a large foam at the water/air interface. The foam becomes denser with time [24]. As seen in Fig. 2, it appears that EF efficiency is highly dependent on t_{EF}.

3.3.2. Current density effect

The current density, i, is a critical parameter in electrochemical processes. Current intensity I (A), and consequently i (A/m^2), can be directly controlled and determine the production rate of gas bubbles. The bibliographic sources report that i is between 10 and 150 A/m^2 and the high values are desirable for liquid/solid separation process [25]. The effect of this parameter on the microalgae elimination is indicated by the curve shown in Fig. 3. The current densities applied are: 29, 103, and 170 A/m^2 corresponding to the following applied voltages U (V): 4, 8, and 12 V, respectively. The release of hydrogen and oxygen bubbles and the density of the formed foam increase with i. As seen in Fig. 3, the microalgae elimination grows with i. As i increases, the release of gas bubbles formed at the electrodes increase. It is clear that the

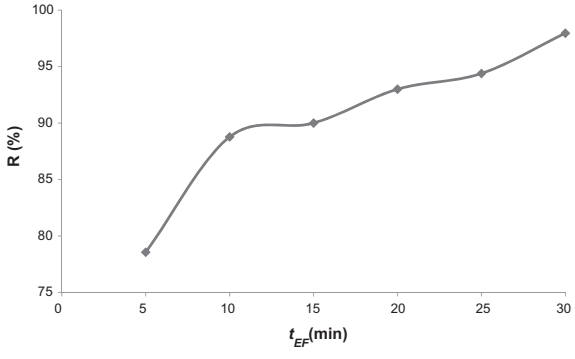

Fig. 2. Algae removal as a function of t_{EF} (pH 7,8, $i = 29$ A/m^2, $d = 2$ cm).

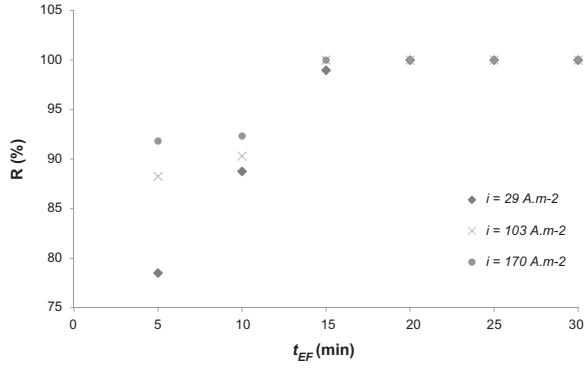

Fig. 3. Effect of current density i on EF efficiency (pH 7.8, $d = 2$ cm).

influence of i is large (Fig. 3). Indeed, after 5 min, the percentage reduction is reached over 90% for $i = 170\ A/m^2$. Moreover, it has been shown that the size of gas bubbles released from the electrodes decreases with increasing i leading to faster and more efficient flotation of microalgae [25].

3.3.3. Initial pH effect

It is well known that pH is one of the main factors that control the electrochemical performance. As shown in Fig. 4, the elimination of microalgae by EF is effective throughout the pH range selected. Indeed from pH 4 to 10, R(%) is between 65 and 100%. So it is better to treat the GD waters in the neutral range, i.e. without pH adjustment. In terms of microalgae reduction, Fig. 4 shows two distinguished pH intervals: pH 4 and 6, and pH 7.8 and 10. For acidic pH, EF efficiencies are less important than for alkaline pH.

Vandamme et al. [26] investigated the potential of flocculation induced by high pH for harvesting *Chlorella vulgaris*. They demonstrated that flocculation can be induced by increasing medium pH to 11. The same approach is used by Wu et al. [27]. Henderson et al. [28] measured the zeta potential at optimum removal by coagulation and flotation of four species of algae and observed that when the zeta potential was reduced between –8 and +2 mV through a combination of coagulant dose and/or pH adjustment, the removal of algae and associated organic material was optimised, irrespective of the coagulant dose or pH. Process control using zeta potential is therefore a viable tool for algae removal [29]. A similar study is performed by Rashid et al. [30] who used chitosan as a flocculant to harvest freshwater microalgae *C. vulgaris*. They showed that pH 6.0 is the highest harvesting efficiency (99%). Their measurement of zeta potential confirmed that the flocculation was induced by charge neutralisation. One may ask this question if in the natural pH (i.e. 7.8) for GD water (pH 7.8) are we not in the "reduced zone" of microalgae zeta potential during EF process? Wang et al. [31] investigated the effect of pH adjusted by aeration with carbon dioxide (CO_2) on the growth of two species of blue–green algae, *Microcystis aeruginosa* and *Anabaena spiroides*. They found that three conditions (pH 5.5, 6.0, and 6.5) have important inhibitory effects on the growth of the two algae species when acidification treatment was conducted during the logarithmic phase. They also found that *M. aeruginosa* was inhibited significantly, but not dead at pH 6.5, whereas death occurred at pH 5.5 and 6.0.

Moreover, the pH evolution as a function of t_{EF} is registered in Fig. 5. This evolution depends on the initial pH of the solution. As seen in Fig. 5, pH increases if the initial pH is below 7. In contrast, it decreases if the initial pH is above 7. In other words, EF process tends to adjust pH to the neutrality.

3.3.4. Inter-electrode distance effect

One of the parameters influencing the EF treatment is the distance between anode and cathode (called inter-electrode distance). This parameter is evaluated at different times while fixing the other factors. Two distances, $d = 1$ and 2 cm, are imposed by the dimensional characteristic of the experimental device. The results obtained are shown in Fig. 6. By examining the curves presented in Fig. 6, the treatment efficiency increases with decreasing d. Indeed, for $i = 103\ A/m^2$, 95% reduction of microalgae is achieved after only 5 min for $d = 1$ cm at the same time 88% is reached for $d = 2$ cm. On the other hand, after 15–20 min, the EF efficiency is approximately at the same level for both inter-electrode distances.

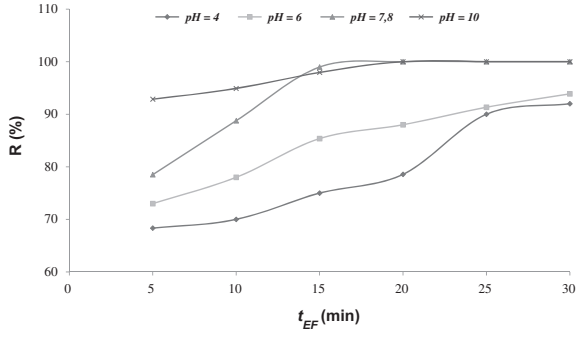

Fig. 4. Influence of pH on EF efficiency ($i = 29\ A/m^2$, $d = 2$ cm).

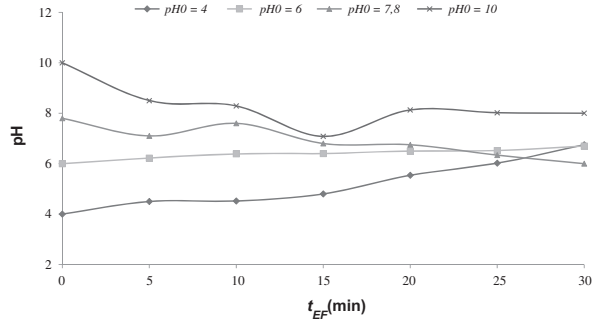

Fig. 5. Evolution of initial pH during EF process (same conditions as those in Fig. 4).

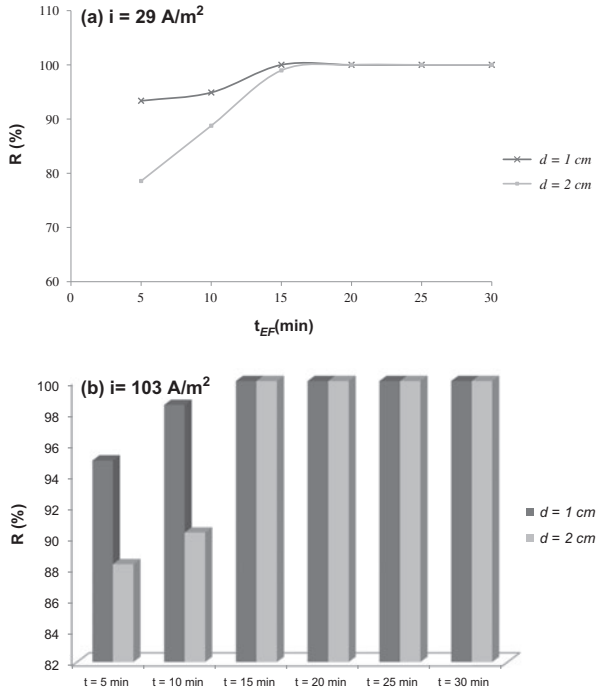

Fig. 6. Influence of the inter-electrode distance d on EF efficiency. (a) $i = 29\ A/m^2$, (b) $i = 103\ A/m^2$.

3.3.5. Cathode fouling

Considering the composition of the GD water (see Table 1), the fouling of cathode must be taken into account. The high total hardness (e.g. 910 mg $CaCO_3$/L during the month of June) has a great risk of fouling formation on the cathode. Changing electrodes polarity may be adopted to avoid the cathode passivation [25].

3.4. Qualitative performance of EF process

Table 2 presents an algological analysis of GD water for April 2011 and treated water by EF at different experimental conditions (E#1-31). By applying the electric current, the numbers and species of algae are reduced as the current density increases (see experiments E#1-10, Table 2). For pH 4 (E#11-16), 6 (E#25-27), 10 (E#17-24) and 7.8 (at $d = 1$ cm, E#28-31), the most important species in the algal population (190 cells in the raw water, Table 2) *Cyclotelle comta* remains as the main survivor species, at the same time the other species are removed relatively faster. Moreover, algae removal is very sensitive to the applied current. For example, for E#1-3, algae are removed even at $29\ A/m^2$. Similar results were obtained by Aragón et al. [32] who applied a similar technique, i.e. electrolysis, for which the current density was only $65\ A/m^2$. Fan et al. [33] evaluated the effectiveness of copper sulphate, chlorine, potassium permanganate ($KMnO_4$), hydrogen peroxide, and ozone on the cell integrity and densities of *M. aeruginosa*. They proved that all of these technologies can compromise the cell membrane of cyanobacteria to varying degrees. In EF process, in the presence of O_2 and H_2, on one hand, and under the action of the electric field, on the other hand, there may be some risks of compromising the cell membrane of microalgae.

On the other hand, electrocoagulation technique, a similar process to EF, has achieved similar efficiencies, i.e. 98–99% [34,35].

For the optimal conditions: $i = 170\ A\ m^{-2}$ ($U = 12$ V, $S_{ra} = 93.5\ cm^2$, $I = i \times S_{ra} = 1{,}59$ A), $d = 1$ cm, $V = 600$ mL, $t_{EF} = 15$ min $= 0.25$ h at pH 7.8 (natural pH), the electricity consumption in the EF tests is considered. The energy consumption is expressed as $kWhm^{-3}$ of the treated water. The electrical energy consumed, E, is calculated as follows:

$$E = \frac{U \times I \times t_{EF}}{V} \tag{6}$$

For the above optimal conditions,

$$E = \frac{12 \times 1.59 \times 0.25 \times 10^{-3}}{0.6 \times 10^{-3}} = 7,95\ kWhm^{-3} \tag{7}$$

3.5. Disinfection by-products (DBPs) formation risks

Disinfection by-products (DBPs) formation in the electrochemical devices has attracted some attention by several authors such as [36–38]. In their review paper, Ghernaout et al. [36] concluded that even at very low chloride concentrations (less than $100\ mg\ L^{-1}$) sufficient free chlorine has a great chance to be electrochemically produced to efficiently disinfect water with the risk of DBPs formation. For these waters, they concluded that well-studied and optimised electric field conditions (such as relatively moderate voltage, elongated residence time, and perfect mixing [37]) must be applied to water/wastewater during electrochemical process (e.g. EF) to avoid or at least reduce the DBPs formation. Further, the chlorinated organics formed due to the partial oxidation in the electrolytic treatment can be removed by passing through activated carbon. Moreover, Pt and boron-doped diamond (BDD) anodes are proved more convenient than other electrodes. Indeed, the great capability of a BDD anode to produce reactive oxygen species and other oxidising

species during the electrolysis allows establishing a chlorine-free disinfection process [39]. Bergmann and Rollin [38] concluded that these electrochemical processes are very complex.

As mentioned above, in order to avoid DBPs formation [40–43], chloride concentration must be less than $100\,mg\,L^{-1}$. As shown in Table 1, chloride concentration in GD water is oscillating between 408 and $540\,mg\,L^{-1}$ during the period of this study, i.e. February–August 2011. The mean value of chloride concentration, $452\,mg\,L^{-1}$, is highly greater than $100\,mg\ L^{-1}$. Consequently, chlorine formation may be added as an additional anodic reaction:

$$Cl^-_{(aq)} \rightarrow (1/2)Cl_{2(g)} + 1e^- \quad E_0 = -1.36\,V \tag{7}$$

Consequently, in the tested experimental conditions, chlorine production is surely present simultaneously with oxygen formation at the anode and hydrogen formation at the cathode. Since electrochlorination is an induced process here, the process studied in this work may be called EF-chlorination instead of EF alone. Moreover, DBPs formation is also not avoided here.

Finally, electrochemical processes for algae removal or harvesting still need more applied researches in the perspective of their industrial applications.

4. Conclusions

From this study, the following points may be drawn:

(1) Since microalgae can behave practically as colloidal particles, and can thus be moved in an electric field, EF is used as an efficient method for their separation from the mass of water. On the other hand, thanks to the lightness of the destabilised algae due to the electric field action, an effect promoted by the fixation of oxygen and hydrogen bubbles, it is proven that the separation of algae from the solution can be carried out by EF rather than decantation. This fact should be taken into account in designing a system of algal separation based on EF.

(2) Future research must focus on microalgae lysis, toxin release and degradation due to EF treatment. The electrolytic conditions in EF process may damage cells and release their toxins in the treated water; in this case, precautions must be taken such as reducing the applied voltage, increasing the residence time in the electrochemical device and/or add a powdered activated carbon adsorption stage.

(3) Chlorine production as a possible secondary reaction in EF device must be controlled and avoided by selecting the applied voltage and appropriate electrodes due to the risk of DBPs formation especially in the presence of natural organic matter or microalgae lysis.

References

[1] D. Ghernaout, The best available technology of water/wastewater treatment and seawater desalination: Simulation of the open sky seawater distillation, Green Sustain. Chem. 3 (2013) 68–88.
[2] D. Ghernaout, B. Ghernaout, On the concept of the future drinking water treatment plant: Algae harvesting from the algal biomass for biodiesel production—A review, Desalin. Water Treat. 49 (2012) 1–18.
[3] B. Ghernaout, D. Ghernaout, A. Saiba, Algae and cyanotoxins removal by coagulation/flocculation: A review, Desalin. Water Treat. 20 (2010) 133–143.
[4] D. Ghernaout, B. Ghernaout, M.W. Naceur, Embodying the chemical water treatment in the green chemistry—A review, Desalination 271 (2011) 1–10.
[5] M. Ma, R. Liu, H. Liu, Chlorination of *Microcystis aeruginosa* suspension: Cell lysis, toxin release and degradation, J. Hazard. Mater. 217–218 (2012) 279–285.
[6] M. Mascia, A. Vacca, S. Palmas, Electrochemical treatment as a pre-oxidative step for algae removal using *Chlorella vulgaris* as a model organism and BDD anodes, Chem. Eng. J. 219 (2013) 512–519.
[7] J. Kim, B.-G. Ryu, K. Kim, B.-K. Kim, J.-I. Han, J.-W. Yang, Continuous microalgae recovery using electrolysis: Effect of different electrode pairs and timing of polarity exchange, Bioresour. Technol. 123 (2012) 164–170.
[8] L. Barsanti, P. Gualtieri, Algae: Anatomy, Biochemistry, and Biotechnology. CRC Press, Taylor & Francis Group, Boca Raton, FL, 2006.
[9] M.R. Teixeira, M.J. Rosa, Integration of dissolved gas flotation and nanofiltration for *M. aeruginosa* and associated microcystins removal, Water Res. 40 (2006) 3612–3620.
[10] B. Koopman, E.P. Lincoln, Autoflotation harvesting of algae from high-rate pond effluents, Agric. Wastes 5 (1983) 231–246.
[11] D. Ghernaout, A. Badis, A. Kellil, B. Ghernaout, Application of electrocoagulation in *Escherichia coli* culture and two surface waters, Desalination 219 (2008) 118–125.
[12] K. Tumsri, O. Chavalparit, Optimizing electrocoagulation-electroflotation process for algae removal, 2nd International Conference on Environmental Science and Technology, IPCBEE, vol. 6, IACSIT Press, Singapore, 2011.
[13] S. Gao, M. Du, J. Tian, J. Yang, J. Yang, F. Ma, J. Nan, Effects of chloride ions on electro-coagulation-flotation process with aluminum electrodes for algae removal, J. Hazard. Mater. 182 (2010) 827–834.
[14] S. Gao, J. Yang, J. Tian, F. Ma, G. Tu, M. Du, Electro-coagulation–flotation process for algae removal, J. Hazard. Mater. 177 (2010) 336–343.

[15] G. Azarian, A. Mesdaghinia, F. Vaezi, R. Nabizadeh, D. Nematollahi, Algae removal by electro-coagulation process, application for treatment of the effluent from an industrial wastewater treatment plant, Iran. J. Publ. Health 36 (2007) 57–64.
[16] A.K. Lee, D.M. Lewis, P.J. Ashman, Harvesting of marine microalgae by electroflocculation: The energetics, plant design, and economics, Appl. Eng. 108 (2013) 45–53.
[17] S. Curteanu, C.G. Piuleac, K. Godini, G. Azaryan, Modeling of electrolysis process in wastewater treatment using different types of neural networks, Chem. Eng. J. 172 (2011) 267–276.
[18] E. Poelman, N. De Pauw, B. Jeurissen, Potential of electrolytic flocculation for recovery of micro-algae, Resour. Conserv. Recycl. 19 (1997) 1–10.
[19] A. Mahmoud, J. Olivier, J. Vaxelaire, A.F.A. Hoadley, Electrical field: A historical review of its application and contributions in wastewater sludge dewatering, Water Res. 44 (2010) 2381–2407.
[20] H. Utermohl, Zur vervollkommung der quantitative phytoplankton-Methoik, Mitt. Intern. Ver. Limnol. 9 (1958) 1–38.
[21] L. Legendre, W.D. Watt, On rapid technique for plankton enumeration, Ann. Inst. Oceanogr. 58 (1971–1972) 173–177.
[22] J. Rodier, L'analyse de l'eau [Water analysis], 8th ed., Dunod, Paris, 2005 (in French).
[23] M. Fouletier, J.-B. Mathieu, P. Noual, Les applications de l'électrochimie à l'hydrométallurgie [Applications of electrochemistry in hydrometallurgy], Edition Pluralis, Paris, 1980.
[24] V.M. Gómez-López, J. Gobet, M.V. Selma, M.I. Gil, A. Allende, Operating conditions for the electrolytic disinfection of process wash water from the fresh-cut industry contaminated with *E. coli* o157:H7, Food Control 29 (2013) 42–48.
[25] P. Holt, G. Barton, C. Mitchell, Electrocoagulation as a wastewater treatment, The Third Annual Australian Environmental Engineering Research Event, November 23–26, Castlemaine, Victoria, 1999.
[26] D. Vandamme, I. Foubert, I. Fraeye, B. Meesschaert, K. Muylaert, Flocculation of *Chlorella vulgaris* induced by high pH: Role of magnesium and calcium and practical implications, Bioresour. Technol. 105 (2012) 114–119.
[27] Z. Wu, Y. Zhu, W. Huang, C. Zhang, T. Li, Y. Zhang, A. Li, Evaluation of flocculation induced by pH increase for harvesting microalgae and reuse of flocculated medium, Bioresour. Technol. 110 (2012) 496–502.
[28] R.K. Henderson, S.A. Parsons, B. Jefferson, Successful removal of algae through the control of zeta potential, Sep. Sci. Technol. 43 (2008) 1653–1666.
[29] A.J. Garzon-Sanabria, R.T. Davis, Z.L. Nikolov, Harvesting *Nannochloris oculata* by inorganic electrolyte flocculation: Effect of initial cell density, ionic strength, coagulant dosage, and media pH, Bioresour. Technol. 118 (2012) 418–424.
[30] N. Rashid, S. Rehman, J.-I. Han, Rapid harvesting of freshwater microalgae using chitosan, Process Biochem. 48 (2013) 1107–1110.
[31] X. Wang, C. Hao, F. Zhang, C. Feng, Y. Yang, Inhibition of the growth of two blue-green algae species (*Microsystis aruginosa* and *Anabaena spiroides*) by acidification treatments using carbon dioxide, Bioresour. Technol. 102 (2011) 5742–5748.
[32] A.B. Aragón, R.B. Padilla, J.A.F. Ros de Ursinos, Experimental study of the recovery of algae cultured in effluents from the anaerobic biological treatment of urban wastewaters, Resour. Conserv. Recycl. 6 (1992) 293–302.
[33] J. Fan, L. Ho, P. Hobson, J. Brookes, Evaluating the effectiveness of copper sulphate, chlorine, potassium permanganate, hydrogen peroxide and ozone on cyanobacterial cell integrity, Water Res. 47 (2013) 5153–5164.
[34] N. Uduman, V. Bourniquel, M.K. Danquah, A.F.A. Hoadley, A parametric study of electrocoagulation as a recovery process of marine microalgae for biodiesel production, Chem. Eng. J. 174 (2011) 249–257.
[35] C.T. Matos, M. Santos, B.P. Nobre, L. Gouveia, *Nannochloropsis* sp. biomass recovery by electro-coagulation for biodiesel and pigment production, Bioresour. Technol. 134 (2013) 219–226.
[36] D. Ghernaout, M.W. Naceur, A. Aouabed, On the dependence of chlorine by-products generated species formation of the electrode material and applied charge during electrochemical water treatment, Desalination 270 (2011) 9–22.
[37] A.M. Polcaro, A. Vacca, M. Mascia, F. Ferrara, Product and by-product formation in electrolysis of dilute chloride solutions, J. Appl. Electrochem. 38 (2008) 979–984.
[38] M.E.H. Bergmann, J. Rollin, Product and by-product formation in laboratory studies on disinfection electrolysis of water using boron-doped diamond anodes, Catal. Today 124 (2007) 198–203.
[39] D. Ghernaout, Advanced oxidation phenomena in electrocoagulation process: A myth or a reality? Desalin. Water Treat. 51 (2013) 7536–7554.
[40] D. Ghernaout, The hydrophilic/hydrophobic ratio *vs.* dissolved organics removal by coagulation—A review, J. King Saud Univ.—Sci. (2013). doi:10.1016/j.jksus.2013.09.005.
[41] D. Ghernaout, S. Irki, A. Boucherit, Removal of Cu^{2+} and Cd^{2+}, and humic acid and phenol by electrocoagulation using iron electrodes, Desalin. Water Treat. (2013). doi:10.1080/19443994.2013.852484.
[42] D. Ghernaout, M.W. Naceur, B. Ghernaout, A review of electrocoagulation as a promising coagulation process for improved organic and inorganic matters removal by electrophoresis and electroflotation, Desalin. Water Treat. 28 (2011) 287–320.
[43] D. Ghernaout, B. Ghernaout, A. Saiba, A. Boucherit, A. Kellil, Removal of humic acids by continuous electromagnetic treatment followed by electrocoagulation in batch using aluminium electrodes, Desalination 239 (2009) 295–308.