

## Electrocoagulation-flotation: a novel proposal for Latin-American water treatment facilities

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### ABSTRACT

Electrocoagulation-flotation (ECF) is a technique that combines the benefits of coagulation, flotation, and electrochemistry and can be very efficient in removing contaminants present in drinking water. The objective of this study was to determine an ideal configuration for an ECF reactor for the treatment of drinking water. A fractional factorial experimental design ( $2^{6-2}$ ) was performed using initial pH, electric current, electrolysis time, agitation, inter-electrode distance, and a number of electrodes as variables. Subsequently, a central composite rotatable design was conducted using the most significant variables of the fractional design, which were initial pH, electrical current, electrolysis time, and a number of electrodes. The response variables analyzed were color removal, electrode mass consumption, sludge production, and energy consumption. The ECF experiment was performed in a batch system with aluminum electrodes in a monopolar parallel configuration. The ECF technique was adequate for treating drinking water with the best treatment conditions at an initial pH of 8.5, an electrical current of 0.25 A, electrolysis time of 12.5 min, and 3 electrodes. Under these conditions, the efficiency of color removal was 86.42%, electrode mass consumption of 0.019 kg m<sup>-3</sup>, sludge production of 0.087 kg m<sup>-3</sup>, and energy consumption of 0.21 kWh m<sup>-3</sup>.

*Keywords:* Drinking water treatment; Electrochemical treatment; Aluminum electrodes; Central composite rotatable design

### 1. Introduction

Water is one of the most important natural resources since it is indispensable for human survival. Access to drinking water is recognized as an essential human right to maintain an adequate living standard and is highly related to the right to physical and mental health, life, and human dignity [1,2]. This is reflected in the new UN Sustainable Development Goals (UN-SDGs). Goal 6 aims to achieve universal and equitable access to safe and affordable drinking water for all [3].

For public supply purposes, surface water must be treated by conventional or advanced technologies. Chemical coagulation techniques are the most used in Latin-American water treatment facilities [4]. These facilities correspond to slightly modified copies of those used in the most industrialized countries since their notable commercial development stimulates the use of their equipment and technology abroad. Because of the poor water quality of surface water sources [5], the increase in population, and physical space restrictions for installation, treatment facilities must be

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modernized for more efficient loading rates, smaller footprint areas, and practical technologies.

Chemical coagulation with aluminum salts is one of the main steps of conventional treatment. Alternatively, electrocoagulation-flotation (ECF) is promising for water treatment. Both techniques aggregate impurities, however, the coagulant dosage method is different. In chemical coagulation, the coagulant comes from the addition of chemical compounds, while in the ECF it is generated by the electrolytic oxidation of metal electrodes.

The ECF technique is a technology for the treatment of public water that combines the benefits of coagulation, flotation, and electrochemistry [6]. In the electrocoagulation process, the coagulant is generated *in-situ* by the electrolytic oxidation of metal at the sacrificial anode, caused by the electrical current maintained between the electrodes [7,8]. At the same time, the formation of hydrogen gas and hydroxyl ions occurs at the cathode through water electrolysis [9,10]. The electrochemical reduction of water at the cathode produces hydrogen microbubbles that promote smooth turbulence in the system, as well as a connection between pollutants and coagulants by adsorption [7,11,12]. Thus, given the lower density of the pollutant-bubble association with respect to water density, the impurities float to the surface of the water in the reactor [13], forming a layer of floating foam containing gas bubbles and particles in the form of sludge [8,14]. Hydrogen bubble fluctuation is an important component of this technique since it increases the efficiency in the removal of pollutants [15].

The electrode materials have a fundamental role in the treatment, especially the anodic electrode [16–18] since the metal which will form the coagulant is derived from it. Iron and aluminum are the materials most used as electrodes, due to their availability, low toxicity, and high valences that promote the efficient removal of pollutants [7,16,18]. Aluminum is one of the most recommended materials because it is more efficient than iron in most cases [8,16,18,19].

When using aluminum electrodes, the ions react with the hydroxides and form monomeric species of an aluminum hydroxide such as aluminum hydroxide(III). The formation of aluminum hydroxide(III) precipitates (with a large specific surface area), provides fast adsorption of organic and volatile compounds and captures colloidal particles [11]. The complexes generated during aluminum dissolution depend on the pH of the solution [7]. Thus, the formation of aluminum hydroxide(III) occurs at a pH ranging from 5 to 9 [20].

The ECF has many advantages, such as the need for simple equipment, easy operation, low retention time, no additional chemical inputs, and low sludge production [21–23]. In addition, studies have demonstrated that the use of ECF can be efficient in water treatment for the removal of specific contaminants present in water, such as boron [24], iron [25], fluoride [26–30], arsenic [31–34], chrome [35], algae [36,37], calcium [38] as well as some water characteristics, such as color, turbidity, biochemical oxygen demand, chemical oxygen demand, and total solids [39,40]. However, this technology has not been evaluated for the treatment of public water supplies in water treatment plants. Thus, this study determined an ideal configuration of an ECF system for the treatment of drinking water. Operational efficiency and

water quality were used to analyze the technical feasibility of applying this technology for the treatment of the supply water.

Considering the efficiency of ECF treatment in removing water contaminants and its operational advantages, the main goal of this study was to determine an ideal configuration for an ECF reactor for the treatment of drinking water. The response variables (color removal, electrode mass consumption, sludge production, and energy consumption) were analyzed as a function of the initial pH, electrical current, electrolysis time, agitation, inter-electrodes distance, and a number of electrodes.

## 2. Materials and methods

### 2.1. Drinking water sample

The water samples were obtained in the Ibicuí-Mirim and Vacacaí-Mirim Rivers, which supply the municipality of Santa Maria, Rio Grande do Sul, Brazil. Table 1 shows the characteristics of the raw water. A mass of 0.3 g of sodium chloride (NaCl) was added to 1.5 L of the sample to increase its electrical conductivity to approximately  $430.0 \mu\text{S cm}^{-1}$ .

### 2.2. Electrocoagulation–flotation reactor

The ECF experiments were conducted on a bench-scale system, (1.5 L). Aluminum electrodes (6.00 cm height  $\times$  10.5 cm width  $\times$  0.05 cm thickness and a submerged area of  $63.0 \text{ cm}^2$ ) were used as anodes and cathodes in the reactor cell, connected to a DC power supply, with adjustable voltage and electrical current. The electrodes were arranged in parallel monopolar configuration, with agitation during the treatment, as presented in Fig. 1.

### 2.3. Analytical measurements

After the electrolysis time, the water was allowed to stand still for 10 min to allow for the total flotation of the flocs produced. The treated water sample was collected a via sampling point, present in the lower portion of the reactor (Fig. 1(6)). The apparent color was determined by a colorimeter, Quimis, Rua Gema, 292, Campanário, 09930-290, Diadema, São Paulo, Brazil (Q406COR), the pH by a pH meter, Tecnopon, Av. Professor Benedito de Andrade, 649, Distrito Industrial Unileste, 13422-000, Piracicaba, São Paulo, Brazil (AC 200), and the electrical conductivity by a conductivity meter, Tecnopon (Luca 210).

### 2.4. Determination of the color removal efficiency

The color removal efficiency was evaluated using Eq. (1) [18,41].

Table 1  
Characteristics of the raw water

Parameter	Value
Color (uC)	74.5
pH	6.8
Electrical conductivity ( $\mu\text{S cm}^{-1}$ )	70.0

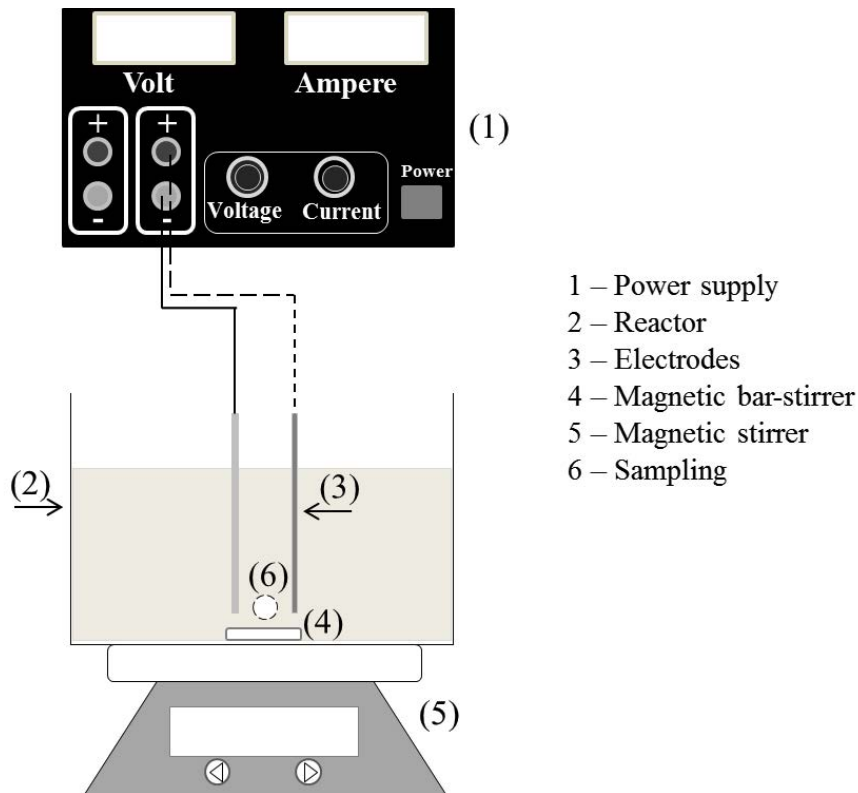


Fig. 1. Reactor ECF on a bench scale with a parallel monopolar electrode connection.

$$\text{Removal efficiency (\%)} = \frac{V_{\text{RW}} - V_{\text{TW}}}{V_{\text{RW}}} \times 100 \quad (1)$$

where  $V_{\text{RW}}$  = value of the parameter in the raw water, and  $V_{\text{TW}}$  = value of the parameter in the treated water.

### 2.5. Energy consumption, electrode mass consumption, and sludge production

The energy consumption was calculated using Eq. (2) [42–44]:

$$C_e (\text{Whm}^{-3}) = \frac{V \cdot i \cdot t}{v} \quad (2)$$

where  $C_e$  is the energy consumption ( $\text{Whm}^{-3}$ ),  $V$  is the voltage (V),  $i$  is the electrical current (A),  $t$  is the electrolysis time (h), and  $v$  is the volume of water ( $\text{m}^3$ ). The production of sludge was calculated using the methodology to determine total solids [45]. The electrode mass consumption was determined experimentally. The electrodes were cleaned with distilled water, dried in an oven ( $105^\circ\text{C}$ ), and weighed using an analytical scale before and after each experiment [8,43].

### 2.6. Experimental design

Factorial designs and response surface analyses are important tools for determining optimal treatment conditions

while allowing simultaneous analysis of each variable effect and interaction [46]. A fractional factorial design was performed using variables that could influence the ECF process, according to the literature. Initial pH, electrical current, electrolysis time, agitation, inter-electrodes distance, and a number of electrodes were evaluated in a fractional design ( $2^{6-2}$ ) with 3 replicates of the central point, resulting in a total of 19 experiments. The levels of the evaluated variables were determined based on preliminary tests and data obtained from the literature. After a fractional factorial design, a central composite rotatable design (CCRD) was set up with the variables that influenced the treatment.

The response variables were: color removal, electrode mass consumption, sludge production, and energy consumption. The results were analyzed using Statistica® 7.0 software (Statsoft Inc., Tulsa, OK, USA) with a significance level of 90% ( $p < 0.10$ ) for the fractional experimental design and 95% ( $p < 0.05$ ) for the CCRD [47].

## 3. Results and discussion

### 3.1. Fractional factorial design

Table 2 shows the results of the fractional experimental design ( $2^{6-2}$ ) where the variables color removal, electrode mass consumption, sludge production, and energy consumption were evaluated as functions of the independent variables which were: initial pH, electrical current, electrolysis time, agitation, inter-electrode distance, and a number of electrodes.

Table 2  
Experimental design ( $2^{6-2}$ ), real values and coded values (in parentheses) and responses

Exp.	pH	EC (A)	ET (min)	Agit. (rpm)	ID (cm)	NE (unit)	pH <sub>f</sub>	CR (%)	EMC (kg m <sup>-3</sup> )	SP (kg m <sup>-3</sup> )	CE (kWh m <sup>-3</sup> )
1	4 (-1)	0.15 (-1)	10 (-1)	220 (-1)	0.5 (-1)	2 (-1)	4.80	-31.46	0.01	0.00	0.05
2	10 (+1)	0.15 (-1)	10 (-1)	220 (-1)	1.5 (+1)	2 (-1)	9.29	-38.99	0.01	0.00	0.09
3	4 (-1)	0.7 (+1)	10 (-1)	220 (-1)	1.5 (+1)	6 (+1)	5.19	-31.86	0.05	0.19	0.47
4	10 (+1)	0.7 (+1)	10 (-1)	220 (-1)	0.5 (-1)	6 (+1)	8.85	76.25	0.06	0.23	0.23
5	4 (-1)	0.15 (-1)	30 (+1)	220 (-1)	1.5 (+1)	6 (+1)	5.63	-151.75	0.05	0.14	0.12
6	10 (+1)	0.15 (-1)	30 (+1)	220 (-1)	0.5 (-1)	6 (+1)	8.78	86.84	0.05	0.21	0.12
7	4 (-1)	0.7 (+1)	30 (+1)	220 (-1)	0.5 (-1)	2 (-1)	6.23	-63.00	0.12	0.29	2.46
8	10 (+1)	0.7 (+1)	30 (+1)	220 (-1)	1.5 (+1)	2 (-1)	9.07	82.63	0.13	0.39	5.01
9	4 (-1)	0.15 (-1)	10 (-1)	430 (+1)	0.5 (-1)	6 (+1)	5.26	-25.48	0.02	0.00	0.02
10	10 (+1)	0.15 (-1)	10 (-1)	430 (+1)	1.5 (+1)	6 (+1)	9.13	-37.00	0.01	0.00	0.04
11	4 (-1)	0.7 (+1)	10 (-1)	430 (+1)	1.5 (+1)	2 (-1)	5.77	-158.04	0.04	0.00	1.75
12	10 (+1)	0.7 (+1)	10 (-1)	430 (+1)	0.5 (-1)	2 (-1)	8.91	72.22	0.04	0.15	0.73
13	4 (-1)	0.15 (-1)	30 (+1)	430 (+1)	1.5 (+1)	2 (-1)	5.70	-179.62	0.03	0.00	0.34
14	10 (+1)	0.15 (-1)	30 (+1)	430 (+1)	0.5 (-1)	2 (-1)	8.86	68.10	0.02	0.15	0.16
15	4 (-1)	0.7 (+1)	30 (+1)	430 (+1)	0.5 (-1)	6 (+1)	7.60	49.05	0.15	0.49	0.70
16	10 (+1)	0.7 (+1)	30 (+1)	430 (+1)	1.5 (+1)	6 (+1)	9.05	87.51	0.15	0.47	1.45
17	7 (0)	0.42 (0)	20 (0)	325 (0)	1 (0)	4 (0)	8.40	88.40	0.06	0.27	0.43
18	7 (0)	0.42 (0)	20 (0)	325 (0)	1 (0)	4 (0)	8.58	92.62	0.07	0.25	0.43
19	7 (0)	0.42 (0)	20 (0)	325 (0)	1 (0)	4 (0)	8.32	92.26	0.07	0.23	0.43

pH – initial pH; EC (A) – electrical current; ET (min) – electrolysis time; Agit. (rpm) – agitation; ID (cm) – inter-electrode distance; NE (unit) – number of electrodes; pH<sub>f</sub> – final pH; CR (%) – color removal; EMC (g) – electrode mass consumption; SP (g) – sludge production; CE (kWh m<sup>-3</sup>) – energy consumption.

Fig. 2a shows the estimated effects of color removal. Only initial pH and the inter-electrode distance had significant effects ( $p < 0.10$ ). The initial pH had a positive effect, which indicates that higher initial pH values favor color removal. Also, the inter-electrode distance produced a negative effect, which indicates that greater color removal is obtained with decreased distance. The electrode mass consumption was positively influenced by electrical current and electrolysis time (Fig. 2b). The variable's electrical current, electrolysis time, and a number of electrodes had a positive effect with respect to sludge production (Fig. 2c). For energy consumption (Fig. 2d), the variable's electrical current and electrolysis time had positive effects while the number of electrodes had a negative effect on the evaluated response variable.

It is important to consider the operational efficiency and quality of the treated water when analyzing the feasibility of using the ECF technique in water treatment plants. The indicator used to evaluate the quality of the treated water was color removal; the indicators used to evaluate the operational efficiency were sludge production, electrode mass consumption, and energy consumption. The variables that most affected the results were electrical current, electrolysis time, and a number of electrodes. Bracher et al. [48] also evaluated the effect of electrical current, electrolysis time, agitation, and inter-electrodes distance in an ECF system and verified that the most influential factors were electrical current and electrolysis time. The high influence of these factors is due to the coagulant dose and the rate of

microbubble generation during ECF. Jose et al. [49] observed a high influence from the number of electrodes over sludge production and energy consumption during the electrocoagulation treatment of effluent generated through the production of coconut fiber. The authors attributed the higher influence of these factors to the effect of reacting surface area in the electrolysis bath. The initial pH was added to these influence variables since it showed the greatest effect on color removal, which is a relevant aspect in the quality and efficiency of treated water, and because it has considerable influence over the process [50,51]. Therefore, initial pH, electrical current, electrolysis time, and a number of electrodes were evaluated in a CCRD ( $2^4$ ) with 8 axial points (experiments 17, 18, 19, 20, 21, 22, 23 and 24, in Table 3) and 4 central points (experiments 25, 26, 27 and 28, in Table 3), totaling 28 experiments.

### 3.2. Central composite rotatable design

Considering the results of the fractional factorial design, a CCRD ( $2^4$ ) was performed to find the ideal operating conditions for the ECF reactor. The response variables for color removal, electrode mass consumption, sludge production, and energy consumption were evaluated as a function of initial pH, electrical current, electrolysis time, and a number of electrodes. The experimental conditions and results are presented in Table 3. The levels of the independent variables were established according to the results obtained in the fractional factorial design.

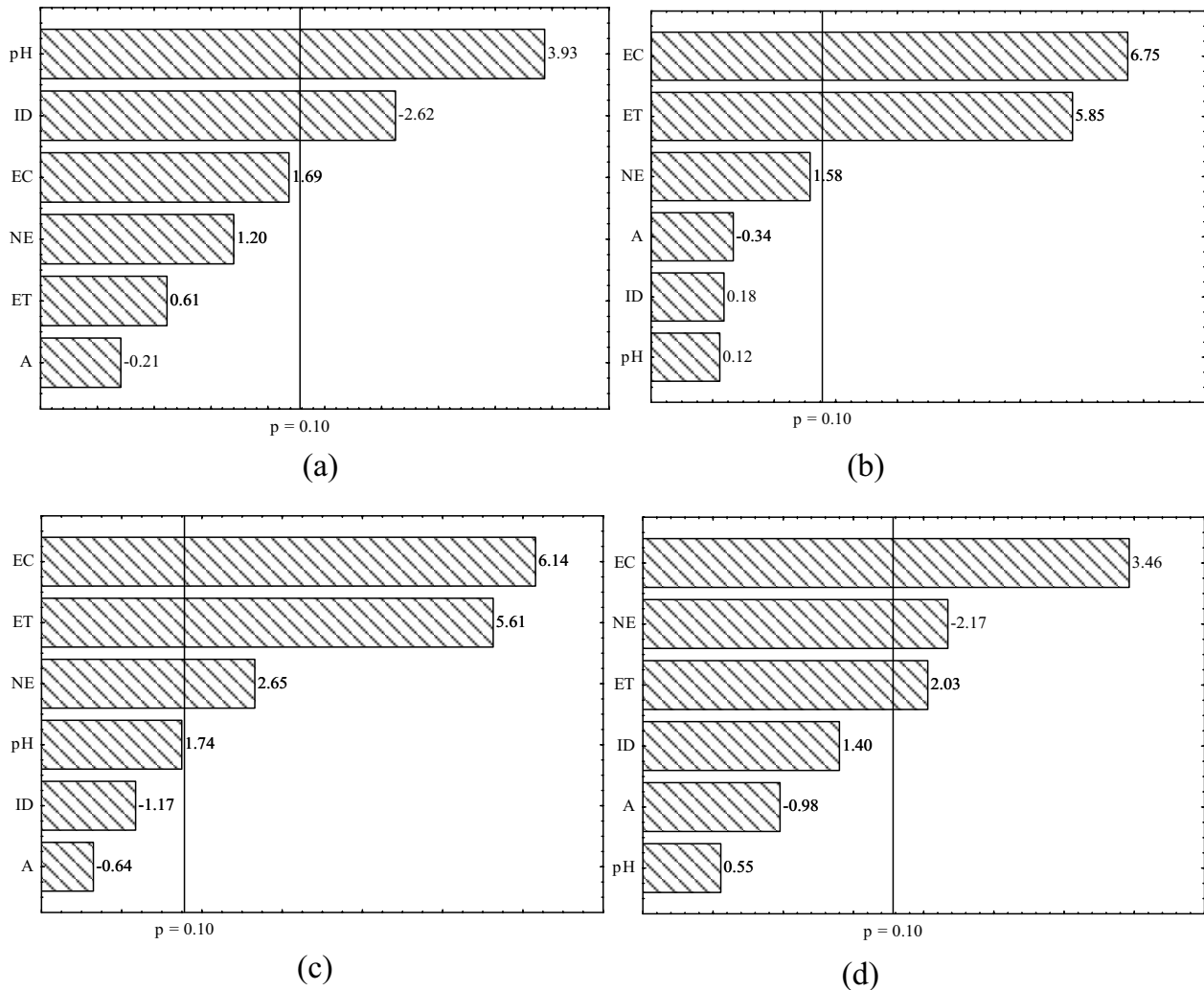


Fig. 2. Pareto chart for the responses, where: EC (electrical current), NE (number of electrodes), ET (electrolysis time), ID (inter-electrode distance), A (agitation), pH (initial pH). (a) Color removal (%), (b) electrode mass consumption ( $\text{kg m}^{-3}$ ), (c) sludge production ( $\text{kg m}^{-3}$ ), and (d) energy consumption ( $\text{kWh m}^{-3}$ ).

An analysis of variance (ANOVA) (Table 4) was used to evaluate whether the experimental results were adequate for the model generation. Values for calculated  $F (F_{cal})$  were superior to those of tabulated  $F (F_{tab})$ , which indicated that the models were statistically significant. Furthermore,  $R^2$  values indicated that the models showed good adjustment to the data obtained. Based on the ANOVA, second-order models were determined to describing color removal, electrode mass consumption, sludge production, and energy consumption [Eqs. (3)–(6)].

$$\text{Color removal (\%)} = 62.72 + 60.56 \text{ pH} - 28.30 \text{ pH}^2 + 21.18 \text{ EC} - 30.90 \text{ pH EC} + 26.49 \text{ EC ET} \quad (3)$$

$$\text{Electrodes mass consumption (kg m}^{-3}\text{)} = 0.06 + 0.02 \text{ EC} + 0.02 \text{ ET} + 0.01 \text{ EC ET} \quad (4)$$

$$\text{Sludge production (kg m}^{-3}\text{)} = 0.19 + 0.02 \text{ pH} - 0.02 \text{ pH}^2 + 0.06 \text{ EC} + 0.07 \text{ ET} + 0.02 \text{ EC ET} \quad (5)$$

$$\text{Energy consumption (kWh m}^{-3}\text{)} = 0.65 + 0.41 \text{ EC} + 0.24 \text{ ET} - 0.19 \text{ NE} + 0.06 \text{ NE}^2 + 0.13 \text{ EC ET} - 0.13 \text{ EC NE} - 0.08 \text{ ET NE} \quad (6)$$

Response surface approaches were constructed based on the second-order models to verify the optimal range for each response variable (Figs. 3a–d). These response surfaces were developed according to the independent variables that were statistically significant for the analysis.

Fig. 3a shows that the best pH values for good color removal were higher than 7.0, and the best electrical current values were less than or equal to 0.4 A.

For low values of electrode mass consumption (Fig. 3b) and sludge production (Fig. 3c), the best conditions were observed with electrolysis times and electrical currents inferior or equal to 12.5 min and 0.25 A, respectively.

Fig. 3d shows that low energy consumption can be obtained with low electrical current values. The influence of the number of electrodes was small when compared

Table 3

Central composite rotatable design, real values and coded (in parentheses). Experimental condition; agitation of 280 rpm; inter-electrode distance of 1.0 cm

Exp.	pH	EC (A)	ET (min)	NE (unit)	pH <sub>f</sub>	CR (%)	EMC (kg m <sup>-3</sup> )	SP (kg m <sup>-3</sup> )	EC (kWh m <sup>-3</sup> )
1	-1 (5.5)	-1 (0.25)	-1 (12.5)	-1 (3.0)	6.08	-44.70	0.018	0.000	0.23
2	1 (8.5)	-1 (0.25)	-1 (12.5)	-1 (3.0)	7.96	86.42	0.019	0.087	0.21
3	-1 (5.5)	1 (0.55)	-1 (12.5)	-1 (3.0)	6.45	-14.43	0.049	0.127	0.90
4	1 (8.5)	1 (0.55)	-1 (12.5)	-1 (3.0)	8.11	89.45	0.042	0.153	0.95
5	-1 (5.5)	-1 (0.25)	1 (27.5)	-1 (3.0)	6.54	-149.67	0.056	0.147	0.46
6	1 (8.5)	-1 (0.25)	1 (27.5)	-1 (3.0)	8.46	90.63	0.054	0.187	0.44
7	-1 (5.5)	1 (0.55)	1 (27.5)	-1 (3.0)	7.39	32.61	0.107	0.287	2.08
8	1 (8.5)	1 (0.55)	1 (27.5)	-1 (3.0)	8.79	85.61	0.117	0.333	1.99
9	-1 (5.5)	-1 (0.25)	-1 (12.5)	1 (5.0)	6.09	-26.83	0.020	0.073	0.14
10	1 (8.5)	-1 (0.25)	-1 (12.5)	1 (5.0)	7.75	74.59	0.020	0.080	0.14
11	-1 (5.5)	1 (0.55)	-1 (12.5)	1 (5.0)	6.15	-28.16	0.031	0.080	0.84
12	1 (8.5)	1 (0.55)	-1 (12.5)	1 (5.0)	8.26	79.65	0.040	0.153	0.47
13	-1 (5.5)	-1 (0.25)	1 (27.5)	1 (5.0)	6.42	-214.26	0.049	0.100	0.28
14	1 (8.5)	-1 (0.25)	1 (27.5)	1 (5.0)	8.26	86.89	0.039	0.133	0.53
15	-1 (5.5)	1 (0.55)	1 (27.5)	1 (5.0)	7.95	70.73	0.097	0.287	1.10
16	1 (8.5)	1 (0.55)	1 (27.5)	1 (5.0)	8.70	85.59	0.106	0.313	1.11
17	-2 (4.0)	0 (0.4)	0 (20.0)	0 (4.0)	5.59	-119.63	0.056	0.073	0.56
18	2 (10.0)	0 (0.4)	0 (20.0)	0 (4.0)	8.93	80.37	0.061	0.193	0.56
19	0 (7.0)	-2 (0.1)	0 (20.0)	0 (4.0)	7.29	71.90	0.017	0.087	0.06
20	0 (7.0)	2 (0.7)	0 (20.0)	0 (4.0)	8.49	77.04	0.103	0.293	1.52
21	0 (7.0)	0 (0.4)	-2 (5.0)	0 (4.0)	7.08	66.37	0.015	0.073	0.13
22	0 (7.0)	0 (0.4)	2 (35.0)	0 (4.0)	8.75	88.25	0.120	0.373	0.97
23	0 (7.0)	0 (0.4)	0 (20.0)	-2 (2.0)	8.22	84.19	0.046	0.193	1.32
24	0 (7.0)	0 (0.4)	0 (20.0)	2 (6.0)	8.39	83.93	0.074	0.227	0.38
25	0 (7.0)	0 (0.4)	0 (20.0)	0 (4.0)	8.04	80.50	0.047	0.153	0.63
26	0 (7.0)	0 (0.4)	0 (20.0)	0 (4.0)	8.27	86.59	0.059	0.187	0.58
27	0 (7.0)	0 (0.4)	0 (20.0)	0 (4.0)	8.16	86.09	0.059	0.193	0.60
28	0 (7.0)	0 (0.4)	0 (20.0)	0 (4.0)	8.32	87.35	0.063	0.227	0.56

pH – initial pH; EC (A) – electrical current; ET (min) – electrolysis time; NE (unit) – number of electrodes; pH<sub>f</sub> – final pH; CR (%) – color removal; EMC (g) – electrode mass consumption; SP (g) – sludge production; CE (kWh m<sup>-3</sup>) – energy consumption.

to electrical current. Greater numbers of electrodes promote lower energy consumption. In experiments 23 and 24 (Table 3) under the same conditions of pH, electrical current, and electrolysis time, the energy consumption for 2 unit electrodes was higher (1.32 kWh m<sup>-3</sup>) than using 6 unit electrodes (0.38 kWh m<sup>-3</sup>). Jose et al. [49] also reported that using a greater number of electrodes promotes lower energy consumption. With 6 electrode units, the authors observed an energy consumption of 0.0057 kWh L<sup>-1</sup>; while using 2 electrode units, energy consumption was 0.0809 kWh L<sup>-1</sup>. Energy consumption was lower as more electrodes were used since the current density is lower under these conditions [52].

Considering all response variables, the ideal treatment condition occurs with a pH higher than or equal to 7, electrical current adjusted to less than or equal to 0.4 A, electrolysis time less than or equal to 12.5 min, and a number of electrodes less than 5 for this current range. Thus, experiment 2 would be the most adequate for the optimal

treatment conditions, which corresponded to a pH of 8.5, an electrical current of 0.25 A, electrolysis time of 12.5 min, and 3 units of electrodes. Under these conditions, 86.42% of color, 0.019 kg m<sup>-3</sup> electrode mass consumption, 0.087 kg m<sup>-3</sup> sludge production, and 0.21 kWh m<sup>-3</sup> of energy consumption were obtained. The electrode mass consumption was low when compared with results obtained by Kumar and Goel [53], Babu and Goel [54], as well as Hashim et al. [26], who found values from 0.036 to 0.15 kg m<sup>-3</sup>. There was also low sludge production, since Essadki et al. [30], Kumar and Goel [53], and Babu and Goel [54] found values from 0.34 to 0.6 kg m<sup>-3</sup>. The reactor also showed low energy consumption when compared with those observed by Zuo et al. [28], Gao et al. [37], Wan et al. [55], Ucar et al. [32], Mohora et al. [56], Sandoval et al. [57], Wiley and Trent [36], Hashim et al. [25], Hashim et al. [26] and McBeath et al. [58], who found values from 0.3 to 5.1 kWh m<sup>-3</sup>; all these studies were applied for water treatment.

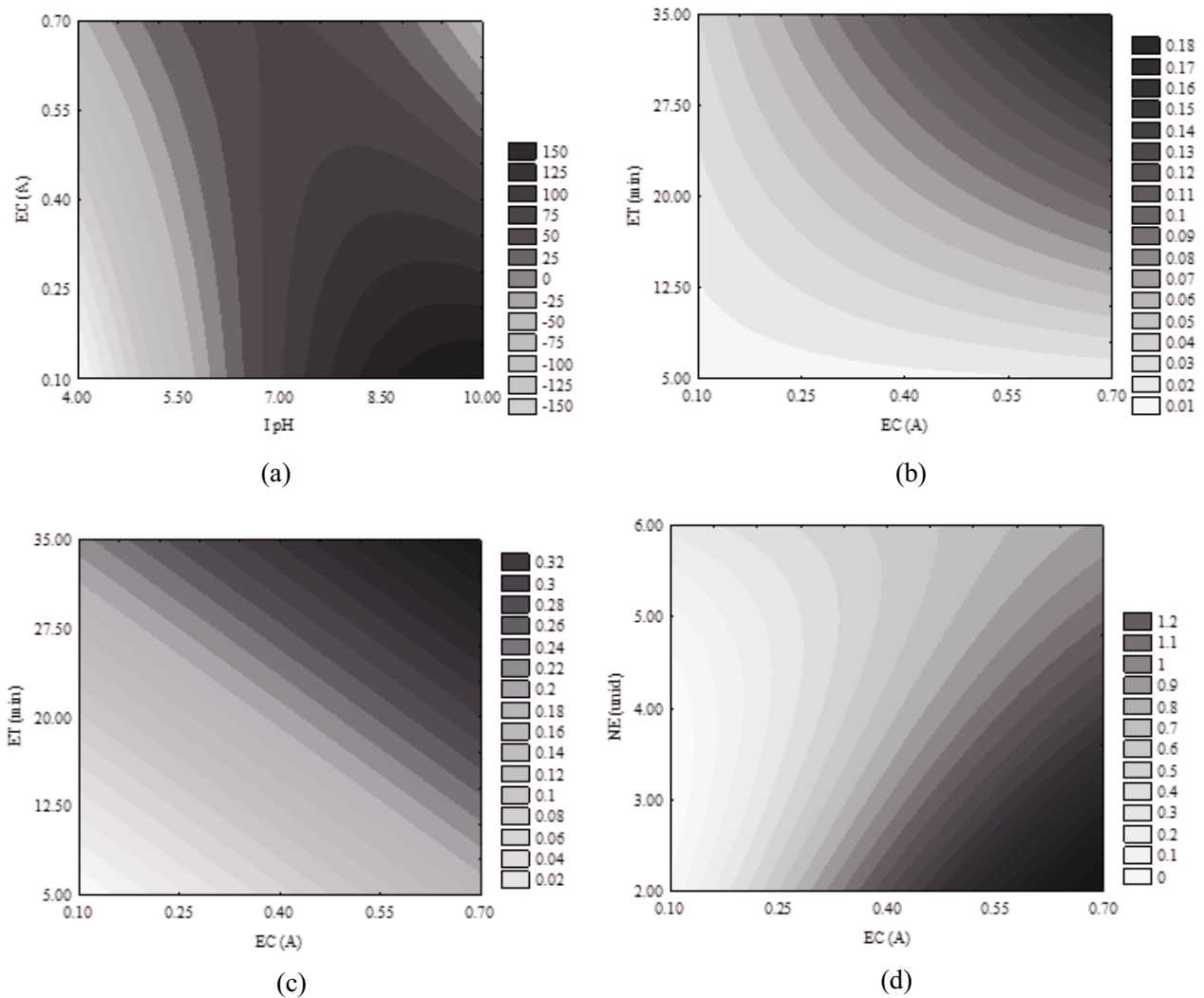


Fig. 3. Response surface for the (a) color removal (%) – agitation 280 rpm; inter-electrode distance of 1.0 cm; electrolysis time of 20 min; 4 electrode units. (b) Electrode mass consumption ( $\text{kg m}^{-3}$ ) – agitation 280.0 rpm; inter-electrode distance of 1.0 cm; pH 7.0; 4 electrode units. (c) Sludge production ( $\text{kg m}^{-3}$ ) – agitation of 280 rpm; inter-electrode distance of 1.0 cm; pH 7.0; 4 electrode units. (d) Energy consumption ( $\text{kWh m}^{-3}$ ) – agitation of 280 rpm; inter-electrode distance of 1.0 cm; pH 7.0; electrolysis time of 20 min.

### 3.3. Effect of the initial pH

The pH can influence the efficiency of ECF treatment [51]. To analyze its influence, experiments were done with acidic (4.0 and 5.5), neutral (7.0), and alkaline pH (8.5 and 10.0). Neutral and alkaline pH promotes higher treatment efficiency [14,59], yet lower pH values (acidic) decrease efficiency [14].

According to Fig. 2, pH showed the highest influence on the treatment of color removal. The experiments conducted with acidic pH produced no satisfactory results, that is, no color removal in most. An acidic pH did not permit the aggregation of particles, which resulted in many suspended precipitates in the clarified water and an increase in water-color. The experiments with neutral and alkaline pH resulted in good color removal efficiency; optimal conditions for sweep coagulation are obtained with pH values between 6 and 8 [60]. The increase from a neutral to alkaline pH did not

achieve better results, which was a positive aspect of water treatment. In other words, the increase in pH is unnecessary, allowing the use of water with natural pH. Thus, besides being efficient in removing pollutants, a neutral pH has the advantage of eliminating the use of additional chemicals for pH adjustment, which reduces environmental risks and treatment costs [51].

Silva et al. [46], Barişçi and Turkay [61] and Nasrullah et al. [62] performed treatments using acid, alkaline, and neutral pH values, finding the most efficient treatment when using a neutral pH value of approximately 7. Cerqueira et al. [43] also observed greater efficiencies of the electrolytic treatment at a pH higher than 6, with satisfactory results at neutral pH.

Table 3 shows that there was an increase in the final pH in treatments with an acidic initial pH, while the final pH decreased with an initial alkaline pH. This

Table 4  
Analysis of variance

	SS	df	MS	$F_{cal}$	$F_{tab}$	$R^2$
Color removal (%)						
Regression	147,270.0	5	29,454.0			
Residue	34,411.4	22	1,564.2	18.8	2.66	
Total	181,681.4	27				0.81
Electrode mass consumption (kg m <sup>-3</sup> )						
Regression	0.025953	3	0.009			
Residue	0.001482	24	0.000	140.0	3.01	
Total	0.027435	27				0.95
Sludge production (kg m <sup>-3</sup> )						
Regression	0.218838	5	0.044			
Residue	0.017194	22	0.000	56.0	2.66	
Total	0.236032	27				0.93
Energy consumption (kWh m <sup>-3</sup> )						
Regression	7.155948	7	1.022			
Residue	0.396919	20	0.020	51.5	2.51	
Total	7.552865	27				0.95

SS – sum of square; df – degrees of freedom; MS – mean square;  $F_{cal}$  – calculated  $F$ -value ( $MS_{regression}/MS_{residual}$ );  $F_{tab}$  – tabulated  $F$ -value ( $F$ -test);  $R^2$  – ( $R$ -squared).

indicates a buffering effect during treatment. This ability can be attributed to the balance between the production and consumption of hydroxyl ions and the need for charge neutralization before the final transformation of aluminum compounds soluble in aluminum hydroxides [10,61,63]. This behavior occurred in all experiments aside from experiments 8 and 16, possibly due to a higher amount of hydroxyl ions (OH) released in the electrolytic reaction of water hydrolysis at the cathode [11].

### 3.4. Effect of the electrical current

The electrical current is a very important variable for treatment since it determines the production of *in-situ* coagulants, energy consumption [16,64], and the density production of electrolytic bubbles, important factors for flotation [10,15]. In the CCRD (2<sup>4</sup>), the experiments were carried out with different values of electrical current: 0.10, 0.25, 0.40, 0.55, and 0.70 A. A significant influence of the electrical current on the mass consumption of the electrodes, sludge production, and energy consumption was observed (Fig. 2).

The electrical current had a significant effect on all the CCRD (2<sup>4</sup>) responses. The increase of the electrical current caused an increase in electrode mass consumption, sludge production, and energy consumption, which is not desirable for treatment [8,43]. Analogously, an increase in color removal efficiency resulted in an increase in electrical current. However, low electrical current values, such as 0.25 A, have also provided satisfactory color removals.

### 3.5. Effect of electrolysis time

The increase in treatment efficiency is proportional to the electrolysis time due to the higher production of hydroxyls

and metal ions on the electrodes [62]. Based on Faraday's Law, the amount of coagulants released by the electrodes tends to increase with electrolysis time [65]. The electrolysis times of 5.0, 12.5, 20.0, 27.5, and 35.0 min were included in the CCRD (2<sup>4</sup>). According to Table 3, electrolysis time significantly influenced the mass consumption of electrodes, sludge production, and energy consumption. The increase in electrolysis time, experiments 21 and 22 (Table 3), caused an increase in color removal, which is important for treatment efficiency. However, it causes an increase in electrode mass consumption, sludge production, and energy consumption, which are unfavorable for operational efficiency. In order to determine the most adequate electrolysis time, it is important to find equilibrium between all the response variables. In other words, to discover a condition that promotes adequate color removal with low electrode mass consumption, sludge production, and energy consumption.

### 3.6. Effect of the number of electrodes

The electrodes were combined with an anode and a cathode or by several anodes and several cathodes [7]. The experiments were performed using 2, 3, 4, 5, or 6 electrodes. The number of electrodes only influenced energy consumption. In general, greater numbers of electrodes led to less energy consumption. However, Fig. 3d shows that electrical current influences energy consumption, and for electrical currents, up to 0.4 A, the number of electrodes does not significantly change energy consumption.

## 4. Conclusion

The ECF technique produced satisfactory and efficient results for treating drinking water. Considering all the



response variables, the optimal treatment conditions were those applied in experiment 2 (pH 8.5, electrical current 0.25 A, electrolysis time 12.5 min and 3 electrodes), which produced a color removal efficiency of 86.42%, an electrode mass consumption of 0.019 kg m<sup>-3</sup>, a sludge production of 0.087 kg m<sup>-3</sup>, and energy consumption of 0.21 kWh m<sup>-3</sup>. The agitation and inter-electrode distance were not the most significant independent variables when considering all response variables analyzed. The initial pH was statistically significant over color removal. Higher efficiencies were obtained whenever the initial pH had neutral or alkaline values; acidic pH was not adequate. The electrical current had important effects on all response variables. High electrical current values caused high sludge production, and electrode mass and energy consumption. Electrical current values lower than or equal to 0.4 A is more appropriate for water treatment. The number of electrodes particularly influenced energy consumption; a greater number of electrodes promoted lower energy consumption, except for electrical currents below 0.4 A.

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