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Application of electrocoagulation as treatment of slaughterhouse and packing plant wastewater

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ABSTRACT

The growth of the meat industry increases the generation of liquid effluents, which have a high polluting potential due to their chemical composition and it must be treated properly to minimize environmental impacts. One of the most used techniques is electrocoagulation, which uses the principle of electrochemistry where metallic electrodes are immersed in the effluent and connected to a source of electrical energy. To evaluate this technique, effluent from a pig slaughterhouse and packing plant wastewater was treated by electrocoagulation using a bench reactor. Aluminum electrodes were submerged in the effluent using a glass beaker and connected to a direct current source. The tests followed a central composite rotatable design with three independent variables: electric current density, electrolysis time, and distance between the electrodes. The measured color, turbidity, and chemical oxygen demand removal were 97.96%, 98.96%, and 67.44%, respectively. The residual aluminum ranged between 14 and 26 mg L^{-1}. The statistical analysis demonstrated that in the operational condition of 20 min, 5.45 cm between the electrodes and electrical current density of 0.019 A cm^{-2} it was possible to maximize the color removal, reaching 97.12% and at the same time minimize the cost of electrolysis, which is US $1.70 m^{-3}.

Keywords: Color; CCRD; COD; Electroflocculation; Turbidity

1. Introduction

The production of meat is identified as one of the industry sectors that uses the largest amount of water to perform their activities, therefore generating a significant volume of wastewater containing a high concentration of pollutants. According to Bustillo-Lemcopte; Mehrvar [1] effluents are composed of fat, fibers, proteins in addition to blood, stomach, and intestinal mucus, these being the main responsible for the contamination of the effluent.

Due to these characteristics, it is essential to carry out appropriate treatment, ensuring that the release of effluents of this nature causes the least possible impact. Sahu et al. [2] mentioned several techniques that can be applied to effluent treatment, arguing that electrocoagulation is one of the best among them, since it offers an alternative to chemical coagulants and removes colloids, particles, metals, and soluble inorganic pollutants.

Electrocoagulation can be defined as the destabilization and coagulation of suspended, dissolved or emulsified contaminants in an aqueous medium, due to the introduction of electric current in the medium. The electrocoagulation unit consists of an electrolytic cell with two sacrificial electrodes, an anode and a cathode, which can be made of the same metal. The process occurs due to the application of electric

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current to the electrodes, causing the generation of coagulant agent and gas microbubbles [3].

Several factors influence electrocoagulation, including:

Electric current: which is one of the main control factors of the system, influencing the formation of coagulant and also gas microbubbles. High current density leads to a greater formation of the coagulating agent, increasing the removal of pollutants. However, operating the system with a very high electric current may not be the best option, as this results in high consumption of electrical energy, increasing the cost of the treatment [2–4].

Electrolysis time: the production of ions that will form the coagulant is proportional to the electrolysis time and the electric current, according to Faraday's Law. Khandegar and Saroha [4] argue that the pollutant removal increases with increase in electrolysis time, however, close to the optimal point of the electrolysis time removal becomes constant so that the increased time does not mean the improvement on the removal.

Distance between electrodes: responsible for controlling the intensity of the medium's electric field. According to Khandegar and Saroha [4], short distances result in a high electrostatic attraction that hinders the formation of coagulant, while very long distances cause the electrostatic attraction to decrease, decreasing the movement of ions, reducing the removal of the pollutant. For Sahu et al. [2] the distance also influences the cost of treatment, as reduced distances require less energy consumption and smaller reactor size.

Several studies report the use of electrocoagulation to perform the treatment of various effluents, demonstrating the potential that the technique has as a treatment alternative.

Valente et al. [5] evaluated the electrocoagulation applied to dairy effluent by controlling the electrolysis time, current density, distance between the electrodes and initial pH, thus finding removals of 57%, 99%, 92% and 97% for chemical oxygen demand (COD), turbidity, total suspended solids, and volatile suspended solids. The system was operated with a current density of 61.6 A m^{-2}, time of 21 min, and initial pH of 5. The distance between the electrodes was reported as not significant in this study for removing organic matter. However, the authors found that shorter distances provide lower electricity costs.

Fadali et al. [6] used oily effluent to test the electrocoagulation by controlling the electrolysis time, current density, distance between the electrodes, anode diameter, and electrolyte concentration. The treatment efficiency increased with increasing time, current density, electrode diameter, and electrolyte concentration, but decreased when increasing distance between electrodes. The authors recommended using a large distance between the electrodes if the conductivity of the effluent is high, however, this distance should be reduced if the conductivity is moderate.

Mores et al. [7] used digestate to assess the influence of the distance between the electrodes and the potential differential during electrocoagulation. The removals were 97% for color, 98% for turbidity, 77% for total organic carbon, and 10% for total nitrogen operating with a distance of 2 cm between the electrodes and 5 V for 30 min.

Huda et al. [8] studied the effect of the distance between the electrodes, initial pH, and electrolyte concentration in the treatment of raw leachate by means of electrocoagulation. They found the removal of 82.7% for color and 45.1% for COD in the optimal operating condition of 1.16 cm between the electrodes, pH of 7.73, and electrolyte concentration of 2 g L^{-1}.

The works published in the literature presented significant efficiency for the removal of the parameters is varied ranges of operation. However, in most studies, the cost of treatment is not treated as a response variable and this can result in an overestimated financial condition.

The main objective of this study was to evaluate the efficiency of electrocoagulation in the treatment of pig slaughterhouse and packing plant effluent in removing color, turbidity, and COD. In addition, the residual aluminum was quantified and the cost of electrolysis was calculated/estimated, controlling the density of the applied electric current, the electrolysis time, and the distance between the electrodes.

This study was motivated by the interest in knowing the behavior of the cost as a response variable of the statistical analysis, in order to enable its optimization from the controlled variables, seeking to find a relationship between the operational conditions, the cost of treatment, and its efficiency.

2. Materials and methods

2.1. Sample collection

The effluent used to carry out the tests were collected in a swine slaughterhouse and packing plant wastewater, located in the western region of Paraná. The industry slaughters around 6,500 animals per day and generates approximately 5,200 m³ of effluent daily. The treatment in the industry consists of physicochemical operations and biological treatment (Fig. 1). The wastewater collection occurred in the output of the decanters.

2.2. Experimental planning

In order to statistically analyze the results, a central composite rotatable design (CCRD) was set up with three

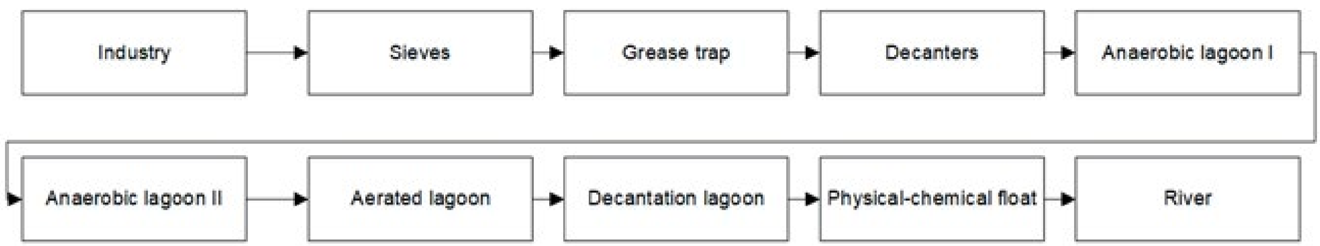

Fig. 1. Effluent treatment adopted by the industry.

independent variables: electrolysis time, the distance between the electrodes, and applied electrical current density, obtaining a complete factorial 2^3 with the addition of six axial points and three repetitions at the central point.

The coded variables X_1 corresponds to the electrolysis time (min), X_2 is associated with the distance between the electrodes (cm) and X_3 represents the density of the applied electric current (A cm^{-2}) (Table 1).

The use of a CCRD type planning allows a more robust statistical analysis of the results, making it possible to calculate the effect of the variables, the errors inherent to the process, and the analysis of variance (ANOVA). It also indicates the quality of the adjustment of the mathematical model generated.

The model was obtained through linear regression of the results. The Eq. (1) represents a generic model for a design with three independent variables, where "β" coefficients are calculated with linear regression, X_n represents the independent variables and the response variable in question are represented by Y.

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 \quad (1)$$

In addition to analyzing the isolated effect of each variable, it is possible to estimate the effect of interaction between them and the presence of quadratic terms allows to optimize the function, finding its maximum or minimum points.

To optimize the process and find a condition that makes it possible to maximize the removal of color, turbidity, and COD at the lowest cost, the desirability analysis was applied, as proposed by Derringer and Suich [9]. This technique simultaneously analyzes the mathematical models obtained in order to obtain the best conditions for all the response variables analyzed.

This is possible since the referred methodology transforms the analyzed responses into a dimensionless scale of individual desirability, which can vary from 0, for unacceptable results, and 1 for the desired result. By making the geometric mean of the individual desires, it is possible to calculate the global desirability, so when calculating levels of the variables that maximize the global desirability, the evaluated conditions are simultaneously optimized [9].

Table 1
CCRD testing matrix

Test	X_1		X_2		X_3	
1	–1	(14′3″)	–1	(3.63)	–1	(0.012)
2	1	(25′57″)	–1	(3.63)	–1	(0.012)
3	–1	(14′3″)	1	(7.27)	–1	(0.012)
4	1	(25′57″)	1	(7.27)	–1	(0.012)
5	–1	(14′3″)	–1	(3.63)	1	(0.026)
6	1	(25′57″)	–1	(3.63)	1	(0.026)
7	–1	(14′3″)	1	(7.27)	1	(0.026)
8	1	(25′57″)	1	(7.27)	1	(0.026)
9	–1.68	(10′)	0	(5.45)	0	(0.019)
10	1.68	(30′)	0	(5.45)	0	(0.019)
11	0	(20′)	–1.68	(2.4)	0	(0.019)
12	0	(20′)	1.68	(8.50)	0	(0.019)
13	0	(20′)	0	(5.45)	–1.68	(0.008)
14	0	(20′)	0	(5.45)	1.68	(0.030)
15	0	(20′)	0	(5.45)	0	(0.019)
16	0	(20′)	0	(5.45)	0	(0.019)
17	0	(20′)	0	(5.45)	0	(0.019)

2.3. Electrolytic system

A bench batch system was set up to carry out the electrocoagulation process as described by Orssatto et al. [10]. For each test, 0.8 L of effluent was added in a glass beaker and kept in constant agitation with the aid of a magnetic stirrer. Metallic aluminum electrodes 10 cm long and 5 cm wide were completely immersed in the effluent and then connected to a direct current source. The distance between the electrodes was adjusted using an endless screw (Fig. 2).

According to Orssatto et al. [10], the aluminum that is released in solution due to the dissolution of the electrodes undergoes several chemical reactions as described by Eqs. (2) and (3). However, the formation of aluminum compounds is influenced by the pH, so if the pH is less than 4 the predominant form is the ion Al^{3+}. For pH greater than 10 the formation of aluminate anions occurs. Lastly, in the pH range of 4–10, there is formation of aluminum hydroxide $Al(OH)_3$.

$$Al \rightarrow Al^{3+} + 3e^- \quad (2)$$

Fig. 2. Batch electrocoagulation system.

$$Al^{+3} + 3H_2O \rightarrow Al(OH)_3 + 3H^+ \quad (3)$$

Aluminum hydroxide can be considered an amorphous compound, making it a powerful coagulating agent, due to its extensive surface area that acts by adsorbing organic compounds and capturing colloids [11]. This material is easily accessible and does not provides extra color to the treated effluent.

2.4. Physicochemical analysis

The removal of organic matter was quantified by means of COD and the removal of color and turbidity. The residual aluminum in each test was also determined.

The raw effluent was also characterized by means of pH and conductivity. All methodologies followed the standards of Standard Methods [12] (Table 2).

2.5. Cost of electrolysis

The cost of electrolysis was calculated following the methodology proposed by Orssatto et al. [10]. For this reason, the consumption of the electrodes was considered since due to the oxidoreduction process the dissolution of the metal occurs, and the energy consumption associated with the application of the electric current.

The consumption of the electrodes is calculated according to Faraday's Law, which states that the applied current is proportional to the amount of mass lost. Such a quantity can be estimated using Eq. (4):

$$M_{Al} = \frac{i \cdot T \cdot M}{e \cdot F \cdot V} \quad (4)$$

where M_{Al} is the mass of metal consumed by volume (kg m^{-3}), i is the applied electric current (A), T is the electrolysis time (s), M is the molar mass of the electrode metal (26.98 g mol^{-1}), e is the number of electrons involved in the reaction (3), F is the Faraday's finding (96,500 s A mol^{-1}), V is the volume of effluent used in each test (m^3).

Energy consumption is related to the electrolysis time, the applied electric current, and the verified potential difference and can be calculated using Eq. (5):

$$J = \frac{U \cdot i \cdot T}{V} \quad (5)$$

where J is the energy consumption (Wh m^{-3}), U is the potential difference (V), i is the applied electric current (A), T is the electrolysis time (h), V is the volume of effluent used in each test (m^3).

Within this, it is possible to obtain the total cost of the test using Eq. (6):

$$C_e = aJ + bM_{Al} \quad (6)$$

where C_e is the cost of electrolysis (US \$ m^{-3}), a is the cost of electricity (0.19 US \$ kWh^{-1}), J is the electricity consumption (kWh m^{-3}), b is the cost of aluminum (1.83 US \$ kg^{-1}), M_{Al} is the mass of aluminum consumed (kg m^{-3}).

The economic analysis was based only on the cost of consuming the electrodes and the electrical energy needed for each test, which may vary due to the rate per kWh of the region where the electrocoagulation was applied. As the tests were performed on a laboratory scale the value of construction of the reactor was not considered for this study. For upscale, the cost of the values with the construction of the reactor and other peripheral devices is necessary as inputs, such as electrical lines, wiring, and sludge disposal values.

3. Results and discussion

3.1. Removal percentage

The characterization of the raw effluent resulted in high values for color, turbidity, COD, pH, and conductivity (Table 3). The application of an electrolytic process for treatment is recommended due to its high conductivity since it does not require the addition of electrolytes.

The removal percentages for color, turbidity, and COD is presented in Fig. 3. The percentages for color and turbidity were high, with values above 90% removal. For the COD percentages are in the range of 58%–70%.

For the color, the test with the best results was test number 11, reaching 97.96% removal with an electrical current density of 0.019 A cm^{-2} for 20 min with 2.4 cm between the electrodes. For turbidity, test number 2 stood out with 98.96% removal. This test was performed with an electrical current density of 0.012 A cm^{-2} for 25 m 57 s with 3.63 cm between the electrodes. Test number 5 showed the best COD removal (67.44%), being performed with an electrical current density of 0.026 A cm^{-2} for 14 m 3 s and 3.63 cm of distance between the electrodes.

Cruz et al. [13] studied the efficiency of electrocoagulation in the treatment of pig slaughterhouse effluent, evaluating the performance of aluminum and iron electrodes. The

Table 2
Methods used for physicochemical analyzes

Parameter	Method	Apha (2005)
Color	Spectrometry	2120 C
COD	Colorimetric	5220 D
Turbidity	Nephelometric	2130 B
Residual aluminum	Atomic absorption spectroscopy	3111 D
pH	Potentiometric	4500-H$^+$ B
Conductivity	Conductivity	2510 B

Table 3
Raw effluent characterization

Parameter	Value
COD (mg L^{-1})	3,047
Turbidity (NTU)	386
Color (UC)	4,520
pH	7.67
Conductivity (mS cm^{-1})	2,200

authors have found the removal of around 97% of the COD with a pure aluminum electrode operating with an electrical current density of 0.025 A cm^{-2} and time of 100 min, in addition the aluminum electrode was the least consumed.

The results of the study by Cruz et al. [13] with regard to COD removal were higher than those found in the present study. Analyzing the conditions, it is noticed that the current density was similar to that used, however, the time was significantly higher, which may have contributed to achieve the removal of 97% COD.

Truttim and Sohsalam [14] used effluent from a biodigester to evaluate the efficiency of the electrocoagulation. The maximum COD removal was around 30%, with an aluminum electrode, electric current density of 35 A m^{-2} during 100 min. For color, the removal was around 3% with the same density of the electric current, but in this treatment, the adopted time was 30 min.

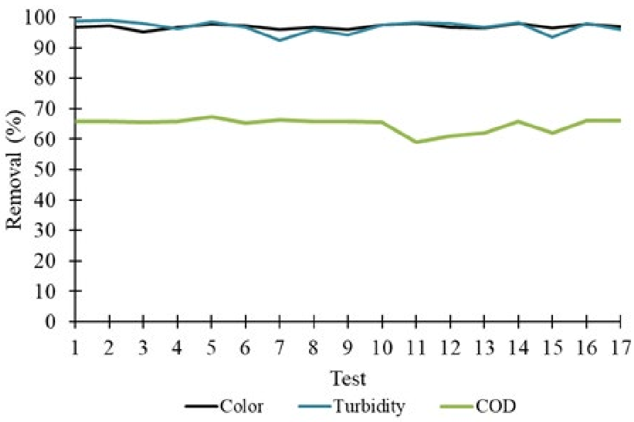

Fig. 3. Removal percentages for color, turbidity, and COD.

The removal of COD obtained by Truttim and Sohsalam [14] was inferior to that found, both for color and for COD. In this case, the authors used electrical current density and electrolysis time higher than those used in this study.

3.2. Statistical analysis

3.2.1. Turbidity

Table 4 shows the regression analysis coefficients for the removal of turbidity. It is noticed that no variable presented significance at a 95% confidence level, since all of them had a *p*-value greater than 0.05.

Regarding the effect of the variables, it was noticed that for X_1 linear, X_2 quadratic, and X_3 quadratic the effect is positive, that is, when the value of these variables increases, the removal of turbidity tends to increase. As for the variables, X_1 quadratic, X_2 linear, and X_3 linear the opposite occurs. The same have a negative effect and increase the value of the aforementioned variables, the removal of turbidity tends to decrease.

In the ANOVA for turbidity removal (Table 5) was found that the mathematical model is not valid, since the *F*-calculated is lower than the *F*-tabulated. This means that the model does not describe the behavior of the results for removing turbidity.

3.2.2. Chemical oxygen demand

The regression analysis for the COD removal indicated that none of the variables obtained a *p*-value less than 0.05, therefore they are not significant with 95% confidence (Table 6).

Table 4
Regression analysis for the removal of turbidity

Factor	Effect	Standard error	*t*(7)	*p*-value	Regression coefficients
Mean	95.788	1.252	76.491	0.000	95.788
X_1 (L)	0.816	1.177	0.694	0.510	0.408
X_1 (Q)	–0.117	1.297	–0.091	0.930	–0.059
X_2 (L)	–1.672	1.177	–1.420	0.198	–0.836
X_2 (Q)	1.535	1.297	1.184	0.275	0.767
X_3 (L)	–0.851	1.177	–0.723	0.493	–0.426
X_3 (Q)	1.122	1.297	0.865	0.416	0.561
X_1X_2	0.874	1.537	0.569	0.587	0.437
X_1X_3	0.810	1.537	0.527	0.615	0.405
X_2X_3	–0.874	1.537	–0.569	0.587	–0.437

Table 5
ANOVA for the removal of turbidity

Source	SS	DF	MS	*F*-calculated	*F*-tabulated	*p*-value
Regression	28.338	9	3.149	0.666	3.677	0.721
Residue	33.071	7	4.724			
Total	61.409	16				

Linear variables X_1 and X_3 had a positive effect, as well as the associated quadratic X_1, X_2, and X_3. By increasing the value of the mentioned variables, it is possible to increase the COD removal. The linear variable X_2 has a negative effect, that is, it is necessary to decrease the value of this variable to increase the COD removal.

The ANOVA for the COD removal regression (Table 7), makes it clear that the mathematical model generated is not valid with 95% confidence, since the F-calculated is lower than the F-tabulated.

3.2.3. Color

The regression analysis for color removal, Table 8, showed that the linear variables X_1, X_2, and X_3 are significant in a 95% confidence interval, since they obtained a p-value less than 0.05.

The linear variables X_1 and X_3, in addition to the interaction factor X_1X_2, have a positive effect. The other variables: X_2 linear, X_1 quadratic, X_2 quadratic, X_3 quadratic, X_2X_3, and X_1X_3 have a negative effect.

The ANOVA for the color regression analysis proved that the mathematical model generated is valid, since the F-calculated value is higher than the F-tabulated one with an R^2 of 0.8289, so the model can be represented by Eq. (7) (Table 9).

$$\begin{aligned}\%\text{Color} = 97.120 + 0.373X_1 - 0.198X_1^2 - 0.464X_2 - \\ 0.002X_2^2 + 0.321X_3 - 0.059X_3^2 + \\ 0.289X_1X_2 - 0.228X_1X_3 - 0.026X_2X_3\end{aligned} \tag{7}$$

Table 6
Regression analysis for the removal of COD

Factor	Effect	Standard error	$t(7)$	p-value	Regression coefficients
Mean	64.525	1.415	45.593	0.000	64.525
X_1 (L)	–0.407	1.330	–0.306	0.768	–0.204
X_1 (Q)	1.966	1.465	1.342	0.222	0.983
X_2 (L)	0.407	1.330	0.306	0.769	0.203
X_2 (Q)	–2.103	1.465	–1.435	0.194	–1.052
X_3 (L)	1.204	1.330	0.905	0.395	0.602
X_3 (Q)	0.716	1.465	0.489	0.640	0.358
X_1X_2	0.451	1.737	0.260	0.803	0.226
X_1X_3	–0.800	1.737	–0.460	0.659	–0.400
X_2X_3	–0.041	1.737	–0.024	0.982	–0.021

Table 7
ANOVA for the removal of COD

Source	SS	DF	MS	F-calculated	F-tabulated	p-value
Regression	42.573	9	4.730	0.784	3.677	0.641
Residue	42.238	7	6.034			
Total	84.811	16				

Table 8
Regression analysis for the removal of color

Factor	Effect	Standard error	$t(7)$	p-value	Regression coefficients
Mean	97.120	0.276	351.261	0.000	97.120
X_1 (L)	0.747	0.260	2.873	0.024	0.373
X_1 (Q)	–0.396	0.286	–1.385	0.209	–0.198
X_2 (L)	–0.928	0.260	–3.570	0.009	–0.464
X_2 (Q)	–0.004	0.286	–0.016	0.988	–0.002
X_3 (L)	0.641	0.260	2.467	0.043	0.321
X_3 (Q)	–0.118	0.286	–0.413	0.692	–0.059
X_1X_2	0.578	0.339	1.703	0.132	0.289
X_1X_3	–0.456	0.339	–1.345	0.221	–0.228
X_2X_3	–0.053	0.339	–0.155	0.881	–0.026

Table 9
ANOVA for the removal of color

Source	SS	DF	MS	*F*-calculated	*F*-tabulated	*p*-value
Regression	7.812	9	0.868	3.769	3.677	0.047
Residue	1.612	7	0.230			
Total	9.424	16				

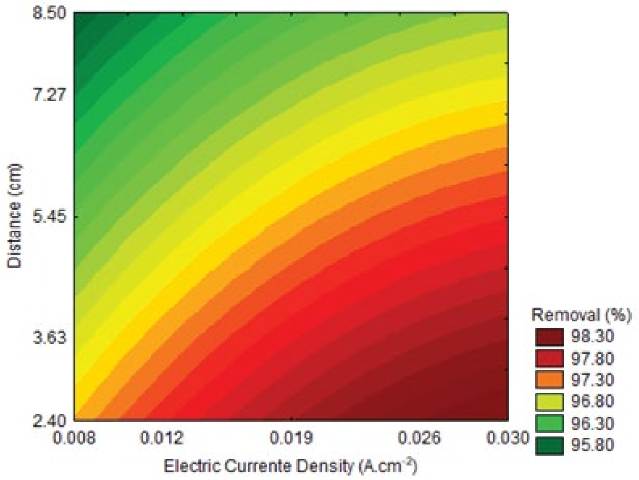

Fig. 4. Contour surface for color removal according to electrical current density and distance between electrodes.

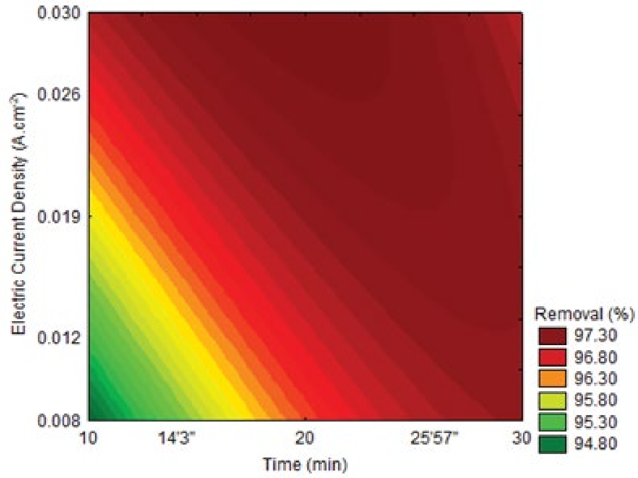

Fig. 5. Contour surface for the removal of color according to the electrolysis time and the electric current density.

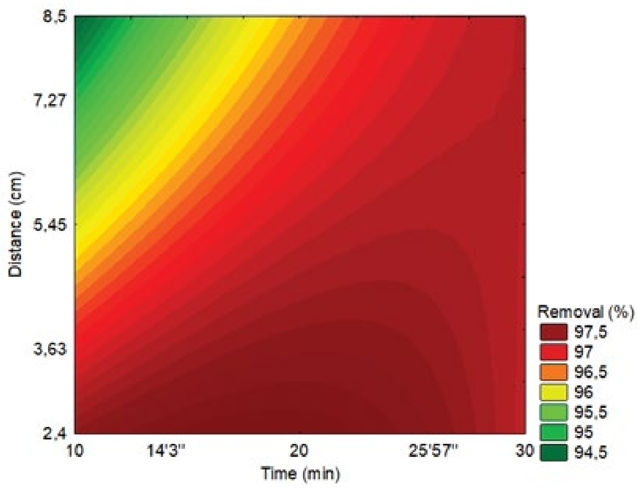

Fig. 6. Contour surface to remove the color according to the electrolysis time and the distance between the electrodes.

Fig. 4 graphically represents the relationship between the density of electric current and the distance between the electrodes. It is noticed that with the increase in the distance between the electrodes the color removal tends to decrease, which is in accordance with the effect evidenced in the regression analysis. As the density of electric current presented a positive effect, the higher the value, the greater the color removal. Thus, the region of greatest removal is in the range of 0.019–0.030 A cm^{-2} for the density of electric current and the distance between the electrodes from 3.63 to 5.45 cm.

The color removal increases as the parameters of electrolysis time and density of electric current pass to a higher level (Fig. 5). The region of greatest removal is between 0.019 and 0.030 A cm^{-2} for the density of electric current and 20–30 min.

Fig. 6 shows the relationship between electrolysis time and the distance between the electrodes. Even with a large distance between the electrodes, it is possible to obtain high removal, as long as the time is high. For distances less than 5.45 cm it is possible to obtain a high percentage of removal regardless of the time. The region that stands out in the removal lies in the time range of 10–25 m 57 s with a distance ranging from 2.4 to 3.63 cm.

3.2.4. Residual aluminum

The residual aluminum concentration is in the range of 14–26 mg L^{-1} (Fig. 7), however, there is no parameter related to the aluminum concentration for the discharge of liquid effluent.

The tests 12 and 13 obtained similar residual aluminum concentration, of 14, 35, and 14.55 mg L^{-1}, respectively. Test 12 was performed with an electrical current density of 0.019 A cm^{-2}, distance of 8.5 cm between the electrodes for 20 min, whereas test 13 was performed with a current density of 0.008 A cm^{-2}, distance 5.45 cm between the electrodes for 20 min.

The highest residual aluminum concentration was 26.79 mg L^{-1} seen in test 6, which was conducted with an electrical current density of 0.026 A cm^{-2}, a distance of 3.63 cm between the electrodes for 25 min 57 s. In test 6, there is an increase in current density and electrolysis time, compared to tests 12 and 13, resulting in an increase in the mass of aluminum consumed [Eq. (4)], where time and electric current are proportional. dissolving the metal.

Vepsäläinen et al. [15] applied electrocoagulation to treat water from the water body, for this purpose they used aluminum electrodes. Analyzing the dissolved aluminum residual, the authors found concentrations in the range of 2–20 mg L^{-1} with application of electric current density of 0.48 mA cm^{-2} and time ranging from 4 to 12 min.

Orssatto et al. [10] treated swine slaughterhouse effluent with electrocoagulation using aluminum electrodes, reporting residual metal from 15 to 54 mg L^{-1} during 25 min with an electrical current density of 21.6 mA cm^{-2}.

Kobya et al. [16] used dye effluent to test the efficiency of electrocoagulation treatment using aluminum electrodes using an electrical current density between 20 and 85 A m^{-2} for 80 min. The residual aluminum ranged from 0.0131 to 0.0392 mg L^{-1}.

Dia et al. [17] studied the treatment of landfill leachate by means of electrocoagulation with aluminum electrodes, reporting 26% increase in aluminum concentration in the treated samples, reaching a concentration of 1.25 mg L^{-1} operating with a current density of 8 mA cm^{-2} for 20 min.

Table 10 shows the results of the regression analysis for the quantification of the aluminum residual in the tests. Only the linear variable X_3 was significant in a 95% confidence interval, in addition it had a positive effect.

The quadratic variables X_1, X_2, and X_3, in addition to the linear variable X_1, had a positive effect, while the linear variable X_2 had a negative effect.

The ANOVA of the regression analysis for the residual aluminum concentration shows that the model is not valid in a 95% confidence interval, since the F-calculated factor is lower than the F-tabulated (Table 11).

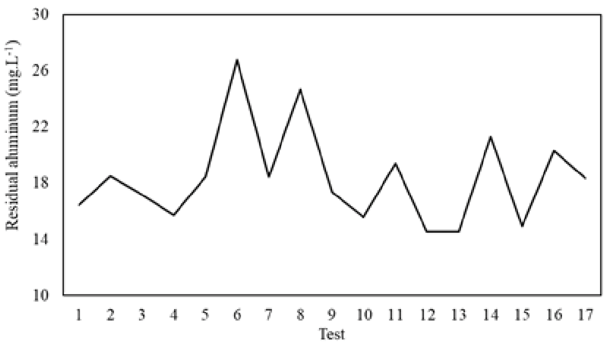

Fig. 7. Concentration of residual aluminum in the tests.

3.2.5. Cost

The cost of each test was calculated using the methodology proposed by Orssatto et al. [10]. Test number 13 obtained the lowest value (US \$0.40 m^{-3}) (Fig. 8). Test 14, on the other hand, resulted in the highest cost of US \$3.79 m^{-3}.

Table 12 shows the regression analysis for the cost of electrolysis, it can be seen that the variables X_1 and X_3 were significant in a 95% confidence interval, since they obtained a p-value less than 0.05. In addition, both had a positive effect, that is, to minimize the cost, it is necessary to decrease the value of the variables.

The variables X_2 linear and X_3 quadratic showed a positive effect, whereas the quadratic variables associated with factor X_1 and X_2 had a negative effect.

Table 10
Regression analysis for residual aluminum

Factor	Effect	Standard error	t(7)	p-value	Regression coefficients
Mean	17.704	1.648	10.745	0.000	17.704
X_1 (L)	1.800	1.548	1.163	0.283	0.900
X_1 (Q)	0.107	1.706	0.063	0.952	0.054
X_2 (L)	–1.814	1.548	–1.171	0.280	–0.907
X_2 (Q)	0.455	1.706	0.267	0.797	0.228
X_3 (L)	4.667	1.548	3.014	0.020	2.333
X_3 (Q)	1.140	1.706	0.668	0.525	0.570
X_1X_2	–1.379	2.022	–0.682	0.517	–0.690
X_1X_3	3.483	2.022	1.722	0.129	1.741
X_2X_3	–0.026	2.022	–0.013	0.990	–0.013

Table 11
ANOVA for residual aluminum

Source	SS	DF	MS	F-calculated	F-tabulated	p-value
Regression	128.535	9	14.282	1.746	3.677	0.237
Residue	57.249	7	8.178			
Total	185.784	16				

The ANOVA for the regression analysis, Table 13, it can be seen that the mathematical model is valid with 95% confidence, since the F-calculated is higher than the F-table, being the same represented by Eq. (8), with an R^2 of 0.8592.

$$\text{Cost}\left(\text{US\$}\cdot m^{-3}\right) = 1.701 + 0.473X_1 - 0.041X_1^2 + 0.135X_2 - 0.302X_2^2 + 0.702X_3 + 0.093X_3^2 + 0.148X_1X_2 + 0.226X_1X_3 + 0.173X_2X_3 \quad (8)$$

Fig. 9 shows the influence of electrolysis time and electrode distance on the cost of each test. Even with high time, it is possible to obtain low costs, as long as the distance between the electrodes is less than 3.63 cm. For distances between 7.27 and 8.4 cm, the cost is minimal if the time is less than 20 min.

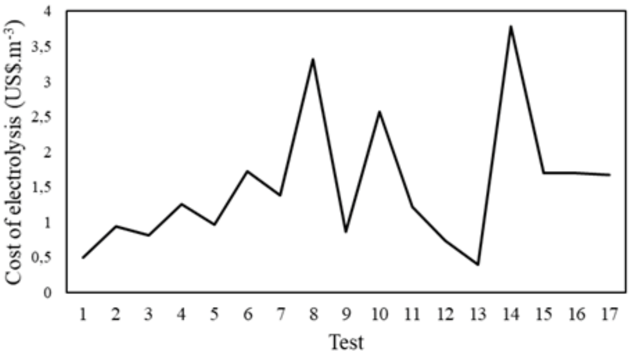

Fig. 8. Cost of electrolysis of the tests.

The region where the lowest costs are found is between 10 and 14 min 3 s, regardless of the distance between the electrodes. This behavior is explained based on the effect of the variables, as time has an effect greater than distance, the variation in time resulting in more pronounced changes in cost.

The graphical representation of the relationship between electrolysis time and the density of the electric current can be found in Fig. 10. It is noted that the range of reduced cost is wide, being possible to obtain a low cost in situations where the current density is high, as long as the time is less than 14 min 3 s. For time values between 10 and 30 min, the current density should not exceed 0.019 A cm^{-2}, so it is possible to define the two regions mentioned as optimal for operation.

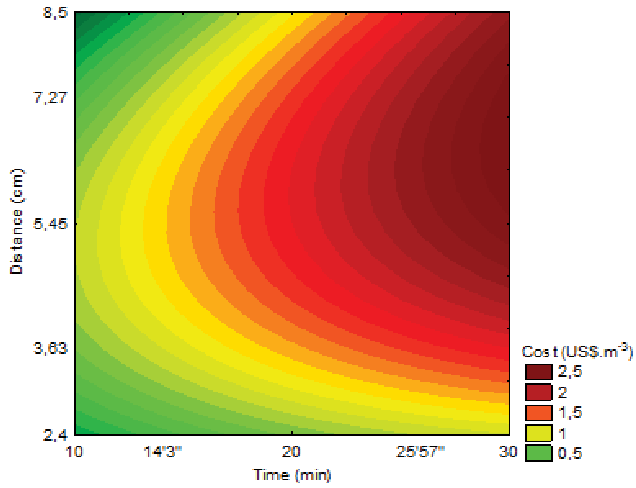

Fig. 9. Contour surface to cost of electrolysis according to the electrolysis time and the distance between the electrodes.

Table 12
Regression analysis for cost of electrolysis

Factor	Effect	Standard error	t(7)	p-value	Regression coefficients
Mean	1.701	0.309	5.504	0.001	1.701
X_1 (L)	0.947	0.290	3.261	0.014	0.473
X_1 (Q)	–0.081	0.320	–0.253	0.807	–0.041
X_2 (L)	0.270	0.290	0.928	0.384	0.135
X_2 (Q)	–0.604	0.320	–1.888	0.101	–0.302
X_3 (L)	1.404	0.290	4.835	0.002	0.702
X_3 (Q)	0.186	0.320	0.581	0.579	0.093
X_1X_2	0.296	0.379	0.780	0.461	0.148
X_1X_3	0.452	0.379	1.193	0.272	0.226
X_2X_3	0.347	0.379	0.915	0.391	0.173

Table 13
ANOVA for cost of electrolysis

Source	SS	DF	MS	F-calculated	F-tabulated	p-value
Regression	12.288	9	1.365	4.747	3.677	0.026
Residue	2.013	7	0.288			
Total	14.302	16				

The interaction between electric current density and distance between the electrodes can be seen in Fig. 11. It is clear that the current density has a more intense influence than the distance in the cost value, being the region where the current density is lower, from 0.008 to 0.019 A cm^{-2} the cost is low regardless of the distance between the electrodes. The opposite occurs for values of density of current exceeding 0.019 A cm^{-2}, where the cost becomes high.

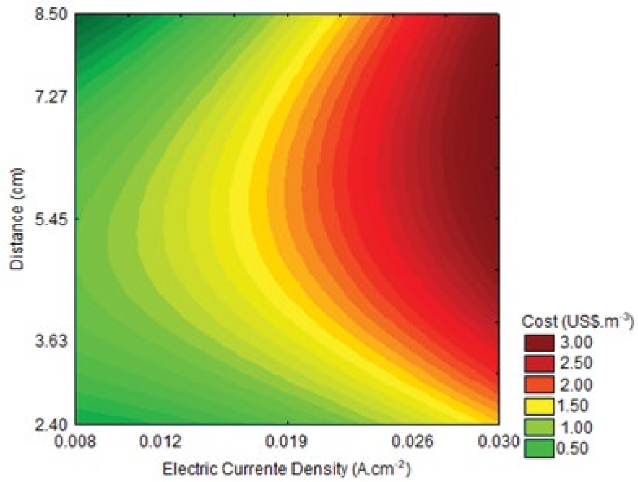

Fig. 11. Contour surface for cost of electrolysis according to electrical current density and distance between electrodes.

3.3. Desirability analysis

The analysis desirability, which has the intention to optimize simultaneously two or more answers, was used to find the condition that would allow maximizing the removal of color with the lowest possible cost.

Fig. 12 shows the desirability to remove the color and cost of electrolysis. The central point (0,0,0) indicated as the ideal condition, with the removal of the color being estimated at 97.12% at a cost of US $1.70 m^{-3}.

In real values, the condition corresponds to an electrolysis time of 20 min with a distance of 5.45 cm between the electrodes and an applied electric current density of 0.019 A cm^{-2}.

4. Conclusions

Thus, it is evident that the electrocoagulation technique can be used to treat effluent from a pig slaughterhouse and packing plant wastewater.

Test 11 achieved the highest color removal (97.96%). As for the removal of turbidity, test 2 obtained the highest

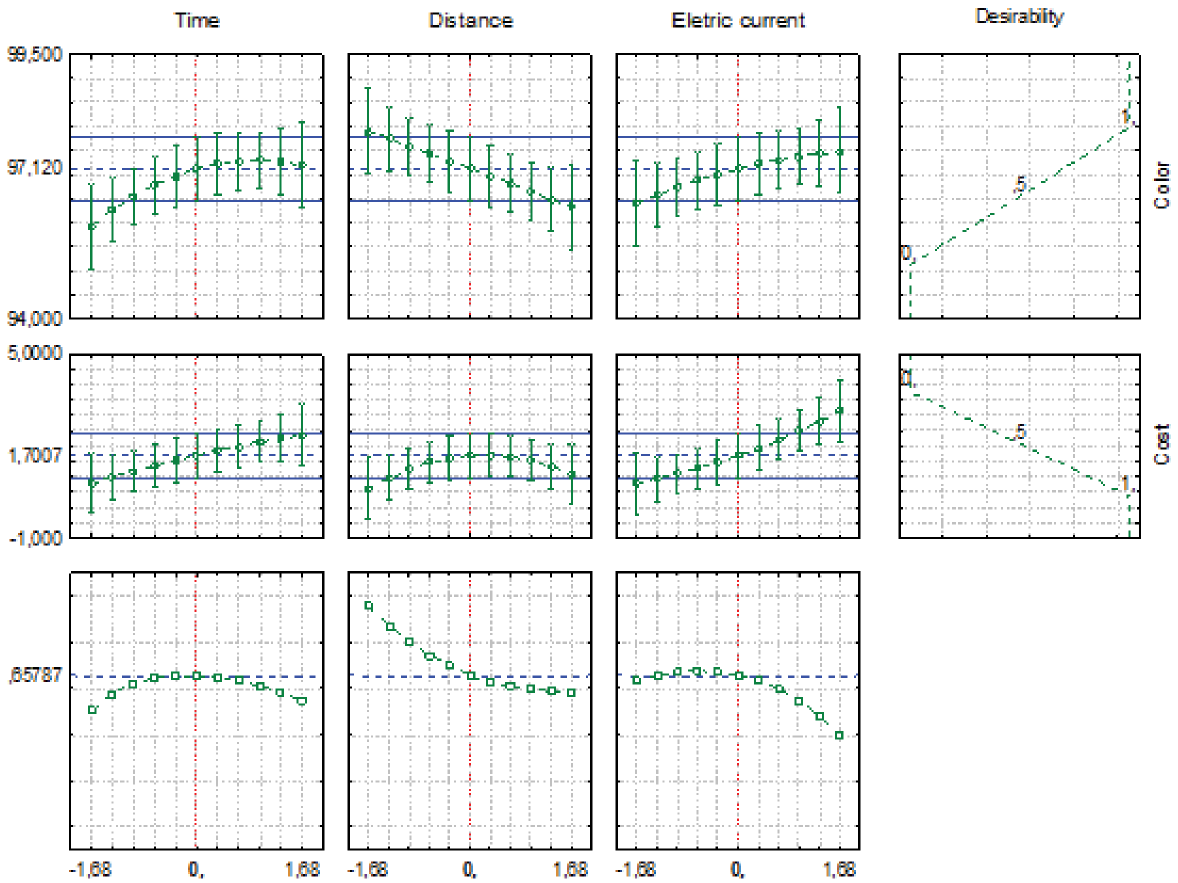

Fig. 12. Desirability analysis for the removal of color and cost of electrolysis.

percentage (98.96%). In the case of COD, the best performance occurred in test 5, reaching 67.44% of removal.

The residual concentration of aluminum varied between 14 and 26 mg L^{-1}. This is a drawback of this method, since aluminum can cause damage to the aquatic ecosystem, and can even affect human health.

The statistical analysis showed that the mathematical models for removing turbidity, COD, and residual aluminum concentration were not valid with 95% confidence, that is, the regression analysis did not fit the data obtained.

The mathematical model for the removal of color and the cost of electrolysis were significant with 95% confidence, making it clear that the models fit the results found. The desirability analysis for the mentioned factors allowed to maximize the color removal and to minimize the cost. The condition equivalent to 20 min of electrolysis, a distance of 5.45 cm between the electrodes and an electrical current density of 0.019 A cm^{-2} is capable of removing about 97.12% of the color at a cost of US $1.70 m^{-3}.

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