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Optimization of the treatment of wastewater from a slaughterhouse and packing plant by the combination of electrocoagulation and tannin-based coagulant

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ABSTRACT

The aim of this paper was to evaluate the removal of chemical oxygen demand (COD), turbidity, color, and total Kjeldahl nitrogen (TKN) of effluents from a pig slaughterhouse and packing plant by the electrocoagulation/organic coagulation combination, and optimize the electrical current, hydraulic retention time (HRT), and concentration of tannin-based coagulant in a batch reactor. The electrocoagulation treatment system consists of a batch reactor with aluminum sacrificial electrodes, organic coagulant, and the effluent to be treated. The electrodes were connected to a direct current source. The adopted experimental design was a rotatable central composite design. For the color, the removal efficiency values ranged from 93.45% to 97.82%; turbidity ranged from 85.53% to 98.37%; COD ranged from 57.89% to 64.73%; and TKN ranged from 11.48% to 65.57%. Mathematical models were obtained for color and turbidity removal. In the calculation of the desirability function, the optimized treatment conditions were 10 min for the HRT and 0.68 A for electrical current, corresponding to a current density of 13.6 mA cm^{-2} and a concentration of 0.775 mL L^{-1} for the tannin-based coagulant. The residual aluminum ranged from 0 to 2.11 mg L^{-1} and the cost of treatment was 1.08 US\$ m^{-3}.

Keywords: Tannin; Physical–chemical treatment; Wastewater

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1. Introduction

The meat processing industry produces large volumes of wastewater from the slaughter of animals and cleaning of slaughterhouses and meat processing plants [1]. The meat processing industry uses 24% of the total freshwater consumed by the food and beverage industry and up to 29% of the water demand of the agricultural sector worldwide [2,3].

The amount of volumes from wastewater generated by these industries is highly polluting. Bayramoglu et al. [4] state that the wastewater from meat packing plants mostly contains organic compounds, such as oils and greases, carbohydrates, proteins, and suspended particles. It is extremely important that these effluents get properly handled to minimize environmental impacts. After that, physicochemical treatment is widely used to remove pollutants from wastewater. For the physicochemical treatments, there are some interesting options available, such as electrocoagulation (EC) and organic coagulation.

EC is an electrolytic technique that involves the dissolution of a metal at the anode, with the simultaneous formation of hydroxyl ions and hydrogen gas at the cathode, which can be retrieved for use as an energy source or a reagent for other industrial applications [5].

The metal ions produced by corrosion of Al or Fe behave similarly with those same ions in the chemical coagulants.

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However, the characteristics of aggregates of the flakes generated during the EC process differ dramatically from those generated by chemical coagulation. Thus, the sludge generated in an EC process tends to contain less moisture and to be more shear resistant and more easily filterable [6]. Al-Shannag et al. [7] obtained results indicating that the filterability of the sludge was improved, namely increasing the voltage gradient to have minimum levels of specific resistance to the filtration.

Moreover, EC is more beneficial than chemical coagulation because it requires a lesser amount of chemicals and the salinity of residual water does not increase [6] in addition to presenting higher efficiency of removal of chemical oxygen demand (COD) and total suspended solids (TSS) [8]. In addition, the gas bubbles generated at the cathode can cause the fluctuation of the flakes, which can be easily retrieved [6].

Several studies have used EC to treat different effluents and obtained relevant results. Al-Shannag et al. [9] used EC in the removal of heavy metal ions from metal plating wastewater.

Al-Shannag et al. [10] when applying EC in the treatment of baker's yeast wastewater, reduced 85% COD.

However, since wastewater treatment by EC requires electric energy, it can be too expensive and not able to apply. To minimize these disadvantages, EC can be combined with other treatment techniques.

The use of organic coagulant combined with EC is an interesting option to remove high levels of pollutants from meat packing and slaughterhouse effluents and reduce electricity costs.

Organic coagulants are new agents that enable to overcome the disadvantages of traditional chemical products. Tannins are considered as a promising source of new coagulating agents. They are water-soluble polyphenolic compounds, mainly of vegetable origin, with a molecular weight ranging from 500 to 1,000 Da [11].

The commercial organic coagulant used to treat effluents is usually based on tannin extracted from plants, such as *Acacia decurrens*, known as black wattle.

Several authors have sought to extract tannins for the removal of pollutants in wastewater. Sánchez-Martíns et al. [12] optimized the synthesis of tannin extracted from *Schinopsis balansae* and tested the coagulant for the removal of dyes and detergents. Skoronski et al. [13] studied the application of tannin in water treated for supply, captured in river Tubarão.

The combination of EC and chemical coagulation has been successfully tested by other authors. Al-Shannag et al. [8], using EC and chemical coagulation in the treatment of wastewater paper industries, increased significantly the removal of COD and TSS.

Thus, the aim of this article is to increase the removal of COD, turbidity, color, and total Kjeldahl nitrogen (TKN) of effluents from a pig slaughterhouse and packing plant by combining EC/organic coagulation and optimizing the electrical current, hydraulic retention time (HRT), and concentration of tannin-based coagulant in a batch reactor, and to calculate the cost of electrolysis and the residual aluminum in the treated effluent.

2. Materials and methods

2.1. Effluent of pig slaughterhouse and packing plant

The effluent used in this study came from a pig slaughterhouse and packing plant located in the western region of the Paraná State, Brazil. This industry slaughters about 6,500 animals, producing an output of 5,200 m^3 of effluent every day.

Fig. 1 shows the flowchart of the wastewater treatment stations of the company.

The wastewater used for the EC experiments was collected after it exits from the decanters/grease traps and characterized, observing the parameters presented in Table 1.

2.2. Experimental batch system

The EC treatment system consists of a bench batch reactor (glass beaker of 1 L and magnetic agitator), which comprised the aluminum sacrificial electrode, the organic coagulant, as well as the effluent to be treated. The electrodes were connected to a direct current source for the EC.

The aluminum electrodes were chosen because, when tested, the iron electrodes added color to the treated effluent.

The coagulant was a low molecular weight cationic polymer, chiefly of tannin-based plant origin, with a density of 1.053 g cm^{-3} and kinematic viscosity of 160 mm^2 s^{-1} (25°C, Ford cup nº 4).

In the beakers, they were added 800 mL of wastewater and submerged the electrodes. The coagulant was added with a micropipette at the moment electrolysis started. The electrodes were arranged at distances of 7.8 cm, and each plate was 10 cm long and 5 cm wide, totaling an area of 50 cm^2.

Fig. 2 illustrates the system described in the section 2.2.

The best conditions are sought to treat wastewater by testing different values for the variables electric current, HRT, and concentration of tannin-based organic coagulant.

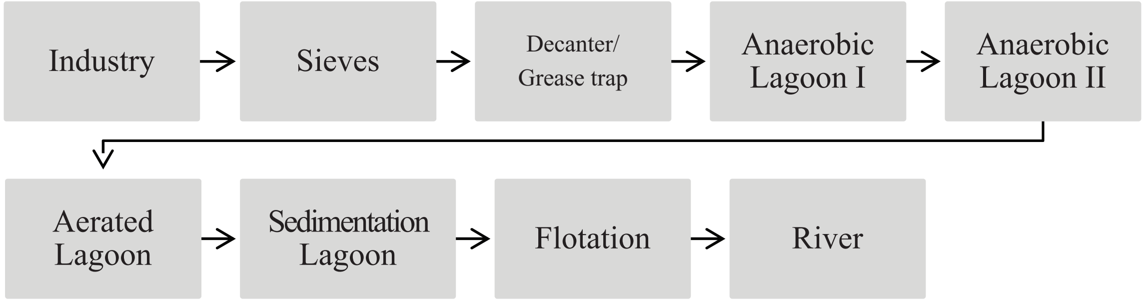

Fig. 1. Flowchart of the slaughterhouse's wastewater treatment station.

Table 1
Physicochemical analysis for effluent characterization

Parameter	Method	Protocol APHA [14]
Chemical oxygen demand, mg L^{-1}	Colorimetric	Method 5220 D
Total aluminum, mg L^{-1}	Flame photometry	Method 3111
pH	Potentiometric	Method 4500 – H^+ B
Electrical conductivity, mS cm^{-1}	Conductivity	Method 2510 B
Turbidity, NTU	Nephelometric	Method 2130 B
Color, µC	Spectrometry	Method 2120 B
Total Kjeldahl nitrogen, mg L^{-1}	Kjeldahl	Method 4500 – N_{org} B

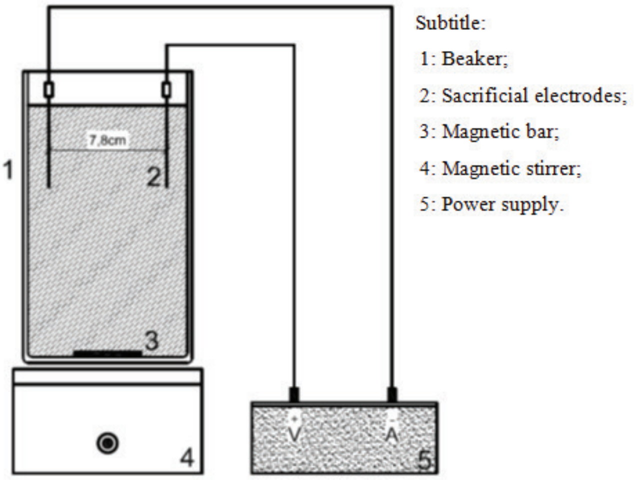

Fig. 2. Experimental module for effluent treatment by electrocoagulation.

2.3. System evaluation

Characteristics such as removal of turbidity, color, COD, and TKN were considered to verify the efficiency of the treatment system. From the obtained data, the efficiency removal of the parameters can be determined according to Eq. (1):

$$\text{Removal } P(\%) = \left[\frac{([VP_i]-[VP_f])}{[VP_i]}\right]\times 100 \quad (1)$$

where $P(\%)$ is the percentage removal of the parameters; VP_i is the parameter value before electrochemical treatment; and VP_f is the parameter value after electrochemical treatment.

Moreover, the aluminum concentration in the treated effluent was analyzed due to concerns with the residual aluminum the electrodes can transfer to the effluent.

2.4. Experimental planning

The experimental design used was the rotatable central composite design (RCCD). As three independent variables were used (HRT, coagulant concentration, and electrical current), performing a complete factorial 2^3, including 6 axial points and 3 repetitions at center point, totaling 17 runs.

Table 2 presents the number of experiments with codified and real values, defined from preliminary tests with the effluent. These tests also showed that the addition of alkaline agents was not necessary and that the effluent had the electrical conductivity necessary to allow the EC to take place.

Table 2
Number of experiments with codified and real values

Experiments	HRT (min)	Coagulant (mL L^{-1})	Electrical current (A)
1	–1 (7.02)	–1 (0.40125)	–1 (0.362)
2	1 (12.98)	–1 (0.40125)	–1 (0.362)
3	–1 (7.02)	1 (0.8475)	–1 (0.362)
4	1 (12.98)	1 (0.8475)	–1 (0.362)
5	–1 (7.02)	–1 (0.40125)	1 (0.838)
6	1 (12.98)	–1 (0.40125)	1 (0.838)
7	–1 (7.02)	1 (0.8475)	1 (0.838)
8	1 (12.98)	1 (0.8475)	1 (0.838)
9	–1.68 (5)	0 (0.625)	0 (0.6)
10	1.68 (15)	0 (0.625)	0 (0.6)
11	0 (10)	–1.68 (0.25)	0 (0.6)
12	0 (10)	1.68 (1.0)	0 (0.6)
13	0 (10)	0 (0.625)	–1.68 (0.2)
14	0 (10)	0 (0.625)	1.68 (1.0)
15	0 (10)	0 (0.625)	0 (0.6)
16	0 (10)	0 (0.625)	0 (0.6)
17	0 (10)	0 (0.625)	0 (0.6)

Based on the results, it was possible to calculate the effect of these variables, the respective errors and the analysis of variance (ANOVA) to verify the quality of the adjustment of the model obtained, relating the response variable to the other independent variables tested, as well as the effect among them. The graphical representation of this model is a surface chart, which supported the determination of the optimum region for the system's operation.

The regression analysis of the data through the RCCD allowed the adjustment of the quadratic models' parameters of the response variables, based on the factors studied and their interactions. Eq. (2) represents a general model to be obtained, with parameters α adjusted through regression analysis.

$$P\ (\%) = \alpha_1 + \alpha_2 x_1 + \alpha_3 x_2 + \alpha_4 x_3 + \alpha_5 x_1 x_2 + \alpha_6 x_1 x_3 + \alpha_7 x_2 x_3 + \alpha_8 x_1^{\ 2} + \alpha_9 x_2^{\ 2} + \alpha_{10} x_3^{\ 2} \tag{2}$$

where P is the percentage removal of the parameters, α is the parameter of the regression model, x_1 is HRT, x_2 is the volume of the tannin-based coagulant, and x_3 is the electric current.

As the study evaluated the removal of five parameters, the simultaneous optimization of response variables was necessary. In order to do that, the desirability function, a methodology created by Derringer and Suich [15] was used.

2.5. Operating cost of electrocoagulation

In the process of EC, the main costs involved are electrode consumption, electricity consumption and labor for operation, maintenance and disposal of the generated sludge.

Since this study was conducted on bench-top scale, consumption of aluminum electrodes and electrical energy and the cost of the tannin-based coagulant were considered to calculate the cost of the process.

Eq. (3) was used to calculate energy consumption.

$$C_e = \frac{U \times i \times t}{V} \tag{3}$$

where C_e is the energy consumption (W h m^{-3}); U is the potential difference applied to the system (V); i is the applied electrical current (A); t is the application time (h); and V is the volume of treated effluent (m^3).

The mass consumption of the electrode (M_{cel}) by volume, during EC, can be quantified by Eq. (4):

$$M_{\text{cel}} = \frac{i \times t \times M}{(F \times n)\ V} \tag{4}$$

where M_{cel} is the mass of electrode consumed mass per volume (kg m^{-3}); i is the applied electrical current (A); t is the application time (s); M is the molar mass of the predominant element of the electrode (26.98 g mol^{-1}); F is the Faraday constant (96,485.3329 s mol^{-1}); n is the number of electrons involved in the anode oxidation reaction (3); and V is the volume of the treated effluent (m^3).

Eq. (5) was used to calculate the amount of tannin-based coagulant.

$$Q_{\tan} = \frac{V_{\tan}}{V} \tag{5}$$

where $Q_{\tan}$ is the amount of coagulant used for volume of treated wastewater (L m^{-3}); $V_{\tan}$ is the volume of coagulant used (L); and V is the volume of the treated effluent (m^3).

With the values of electrode mass, energy consumption, and tannin-based coagulant, it was possible to calculate the operating costs using Eq. (6):

$$C_o = \alpha C_e + \beta M_{\text{cel}} + \gamma Q_{\tan} \tag{6}$$

where C_o is the operation cost (US\$ m^{-3}); α is the cost of electricity (US\$ kWh^{-1}); C_e is the energy consumption (kWh m^{-3}); β is the mass cost of aluminum (US\$ kg^{-1}); M_{cel} is the consumed aluminum mass (kg m^{-3}); γ is the cost of tannin-based coagulant (US\$ L^{-1}); and $Q_{\tan}$ is the amount of coagulant used by volume of treated wastewater (L m^{-3}).

3. Results and discussion

3.1. Characterization of the raw effluent

Table 3 shows the characteristics of the effluent pig slaughterhouse and packing plant used for the experiments.

Bazrafshan et al. [16] characterized wastewater packing plant and found values of 5,817 mg L^{-1} for COD, 7.31 for pH, 3,247 mg L^{-1} for total suspended solids, 9.14 mS cm^{-1} for conductivity, and 137 mg L^{-1} for TKN. The values found in this work and those of other authors reveal that the packing plant effluents have high levels of organic material, among other pollutants.

Corroborating the values found here, Pacheco and Yamanaka [17] state that these effluents are characterized by high organic load due to the presence of blood, manure, undigested stomach contents and intestinal contents, high fat content, and high contents of nitrogen, phosphorus, and salt.

3.2. Removal efficiency

Fig. 3 shows the graph with the removal percentages obtained for color, turbidity, COD, and TKN in the experiments.

In the graph of Fig. 3, the highest removals occurred for the parameters color and turbidity, followed by COD and TKN.

Table 3
Values of effluent characterization parameters

Parameter	Value
Chemical oxygen demand, mg O_2 L^{-1}	2,234.4 ± 146.96
Total aluminum, mg Al L^{-1}	0.0 ± 0.0
pH	7.21 ± 0.0
Electrical conductivity, mS cm^{-1}	2.93 ± 0.04
Turbidity, NTU	725.5 ± 28.99
Color, μC	3,620 ± 42.43
Total Kjeldahl nitrogen, mg N L^{-1}	85.4 ± 1.98

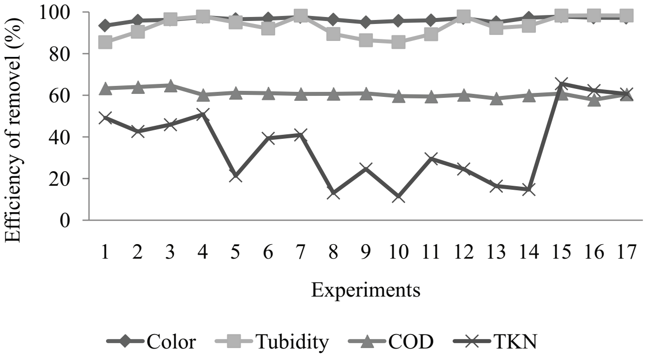

Fig. 3. Removal efficiency of the studied parameters.

Table 4 shows the descriptive statistics of the removal efficiencies for the analyzed parameters, which were calculated based on Eq. (1).

According to Table 4, the lowest and highest removal of color occurred in tests 1 (93.45%) and 15 (97.82%), respectively. For turbidity, the lowest and highest removal occurred in tests 1 (85.53%) and 16 (98.37%), respectively. For COD, the lowest and highest removal occurred in tests 16 (57.89%) and 3 (64.73%), respectively. Finally, for TKN, the lowest removal occurred in test 10 (11.48%) and the highest removal occurred in test 15 (65.57%).

Table 4
Descriptive statistics of the removal efficiencies of turbidity, color, COD, and TKN

	Average (%)	Standard deviation	Minimum (%)	Maximum (%)
Color	96.40	1.14	93.45	97.82
Turbidity	93.26	4.77	85.53	98.37
COD	60.81	1.79	57.89	64.73
TKN	36.07	18.07	11.48	65.57

Bazrafshan et al. [16] treated wastewater from packing plants with the combination: chemical coagulation (polyaluminum chloride) and EC, obtaining removal results of up to 99.78% for COD, 99.61% for BOD, 97.47% for total suspended solids, and 94.89% for TKN. These high removal rates, when compared with the present work, can be explained by the value of electric potential difference (pd) which was 40 V, applied to the treatment.

Orssatto et al. [18], treating wastewater from a pig slaughterhouse and packing plant through EC, obtained removal of 99% for turbidity, 98.83% for color, and 81% for COD, using 25 min of electrolysis time and 1.08 A of electrical current.

3.3. Optimization of the electrocoagulation process

Based on the results, it was possible to assess the mathematical model for the removal of color, turbidity, COD, and TKN.

Tables 5–8 describe the coefficients of the regression model based on the codified matrix. The linear terms are associated with the letter L and the quadratic terms are associated with the letter Q. The parameters with p less than 5% were considered significant.

Table 5
Regression coefficients for the response variable color removal

Factors	Regression coefficient	Standard error	$t(7)$	p Value	Estimates per interval (95%)	
					Lower limit	Upper limit
Average	97.3919	0.23815	408.95	0.000	96.82873	97.95499
x_1 (L)	0.5702	0.22380	2.55	0.038	0.04098	1.09940
x_1 (Q)	–1.2794	0.24655	–5.19	0.001	–1.86245	–0.69641
x_2 (L)	0.9866	0.22380	4.41	0.003	0.45739	1.51580
x_2 (Q)	–0.4671	0.24656	–1.89	0.100	–1.05008	0.11595
x_3 (L)	1.1536	0.22380	5.15	0.001	0.62437	1.68279
x_3 (Q)	–0.7313	0.24656	–2.97	0.021	–1.31435	–0.14831
x_1x_2	–0.6595	0.29228	–2.26	0.059	–1.35067	0.03161
x_1x_3	–1.1361	0.29228	–3.89	0.006	–1.82719	–0.44491
x_2x_3	–1.0048	0.29228	–3.44	0.011	–1.69597	–0.31369

Note: L refers to the linear term, while Q refers quadratic term of Eq. (2).

Table 6
Regression coefficients for response variable turbidity removal

Factors	Regression coefficient	Standard error	$t(7)$	p Value	Estimates per interval (95%)	
					Lower limit	Upper limit
Average	98.1469	1.1202	87.6	0.0000	95.4981	100.7956
x_1 (L)	–1.0142	1.0527	–0.92	0.3674	–3.5034	1.4750
x_1 (Q)	–7.4698	1.1597	–6.44	0.0003	–10.2121	–4.7274
x_2 (L)	4.8918	1.0527	4.64	0.0023	2.4026	7.3811
x_2 (Q)	–2.0807	1.1597	–1.79	0.1158	–4.8230	0.6616
x_3 (L)	0.8929	1.0527	0.84	0.4243	–1.5962	3.3822
x_3 (Q)	–2.6374	1.1597	–2.27	0.0571	–5.3798	0.1049
x_1x_2	–2.3949	1.3748	–1.74	0.1250	–5.6458	0.8560
x_1x_3	–4.5176	1.3748	–3.28	0.0134	–7.7684	–1.2667
x_2x_3	–4.4383	1.3748	–3.22	0.0145	–7.6892	–1.1874

Table 7
Regression coefficients for the response variable of COD reduction

Factors	Regression coefficient	Standard error	$t(7)$	p Value	Estimates per interval (95%)	
					Lower limit	Upper limit
Average	59.5642	1.2607	47.25	0.0000	56.5831	62.5452
x_1 (L)	–0.8953	1.1848	–0.76	0.4745	–3.6968	1.9062
x_1 (Q)	1.3843	1.3052	1.06	0.3241	–1.7021	4.4706
x_2 (L)	–0.2711	1.1848	–0.23	0.8256	–3.0726	2.5304
x_2 (Q)	1.0741	1.3052	0.82	0.4377	–2.0122	4.1605
x_3 (L)	–0.9114	1.1848	–0.77	0.4669	–3.7129	1.8901
x_3 (Q)	0.6476	1.3052	0.49	0.6349	–2.4387	3.7339
x_1x_2	–1.2174	1.5473	–0.79	0.4572	–4.8761	2.4413
x_1x_3	0.9165	1.5473	0.59	0.5723	–2.7423	4.5752
x_2x_3	0.3967	1.5473	0.26	0.8050	–3.2620	4.0554

Table 8
Regression coefficients for the response variable TKN removal

Factors	Regression coefficient	Standard error	$t(7)$	p Value	Estimates per interval (95%)	
					Lower limit	Upper limit
Average	61.4833	9.7899	6.280	0.0004	38.3338	84.6328
x_1 (L)	–4.9115	9.2002	–0.533	0.6099	–26.6666	16.8436
x_1 (Q)	–22.6608	10.1357	–2.235	0.0604	–46.6279	1.3063
x_2 (L)	–1.4513	9.2002	–0.157	0.8791	–23.2065	20.3038
x_2 (Q)	–16.2716	10.1357	–1.605	0.1524	–40.2387	7.6955
x_3 (L)	–11.2167	9.2002	–1.219	0.2623	–32.9718	10.5384
x_3 (Q)	–24.4033	10.1357	–2.407	0.0469	–48.3704	–0.4361
x_1x_2	–8.6065	12.0153	–0.716	0.4970	–37.0184	19.8053
x_1x_3	–2.0492	12.0153	–0.170	0.8694	–30.4611	26.3627
x_2x_3	–2.8688	12.0153	–0.239	0.8181	–31.2807	25.5430

For the response variable color removal, the significant terms were HRT (linear and quadratic terms), coagulant (linear term), electrical current (linear and quadratic terms), and interactions between HRT and electrical current, and coagulant and electrical current. Of these terms, HRT (linear term), coagulant (linear term), and electrical current (linear term) have a positive effect in the model, while the others have a negative effect.

For the response variable turbidity removal, the significant terms were the HRT (Q), coagulant (L), and the interactions between HRT and current, and coagulant and current.

Of these terms, the coagulant (L) had a positive effect in the model, while the others have a negative effect.

The models adjusted for the response variables color and turbidity removal are characterized by Eqs. (7) and (8). For the response variables COD and TKN, it was not possible to obtain the adjusted models.

$$\begin{aligned}\text{Color removal} = 97.3919 + 0.2851x_1 - 0.6397x_1^2 + 0.4933x_2 \\ - 0.2335x_2^2 + 0.5768x_3 - 0.3657x_3^2 - 0.3298x_1x_2 \\ - 0.5680x_1x_3 - 0.5024x_2x_3\end{aligned} \tag{7}$$

$$\begin{aligned}\text{Turbidity removal} = 98.1469 - 0.5071x_1 - 3.7349x_1^2 \\ + 2.4459x_2 - 1.0404x_2^2 + 0.4465x_3 - 1.3187x_3^2 \\ - 1.1975x_1x_2 - 2.2588x_1x_3 - 2.2192x_2x_3\end{aligned} \tag{8}$$

Although some terms are not significant, they were all kept in the models to minimize error.

Tables 9–12 show the ANOVA of the response variable models.

Tables 9 and 10 show that the F calculated for regression is highly significant and the explained variation (R^2) percentages for the models were very good, above 90%. Therefore, it is concluded that the models for the response variables color and turbidity are well adjusted to the experimental data.

For the response variables COD and TKN, Tables 11 and 12 show that the calculated F values were not significant and the variation percentages explained by the models were not good, that is, the models for these variables do not adjust to the experimental data. The response surfaces for COD and TKN removal are not presented in this work.

Figs. 4–6 show the response surfaces for color removal.

Figs. 4–6 reveal that the conditions with the greatest color removal occur approximately in the center point for the HRT,

Table 9
ANOVA for color removal

Variance source	SS	DF	AS	$F_{\text{calculated}}$	$F_{\text{tabulated}}$	p Value
Regression	21.157	9	2.351	13.758	3.677	0.0011
Residue	1.196	7	0.171			
Total		16				

SS = Sum of Squares; DF = Degrees of freedom; AS = Average Square.
Note: % explained variance (R^2) 94.20%.

Table 10
ANOVA for turbidity removal

Variance source	SS	DF	AS	$F_{\text{calculated}}$	$F_{\text{tabulated}}$	p Value
Regression	368.088	9	40.899	10.819	3.677	0.0024
Residue	26.461	7	3.780			
Total		16				

SS = Sum of Squares; DF = Degrees of freedom; AS = Average Square.
Note: % explained variance (R^2) 92.72%.

Table 11
ANOVA for COD removal

Variance source	SS	DF	AS	$F_{\text{calculated}}$	$F_{\text{tabulated}}$	p Value
Regression	20.585	9	2.287	0.478	3.677	0.8506
Residue	33.517	7	4.788			
Total		16				

SS = Sum of Squares; DF = Degrees of freedom; AS = Average Square.
Note: % explained variance (R^2) 34.37%.

Table 12
ANOVA for TKN removal

Variance source	SS	DF	AS	$F_{\text{calculated}}$	$F_{\text{tabulated}}$	p Value
Regression	4,552.836	9	505.871	1.752	3.677	0.236
Residue	2,021.175	7	288.739			
Total		16				

SS = Sum of Squares; DF = Degrees of freedom; AS = Average Square.
Note: % explained variance (R^2) 61.31%.

with coded value 1 for the concentration of coagulant and coded value 0.5 for electric current, corresponding to 10 min, 0.8475 mL L^{-1}, and 0.72 A, respectively.

However, the graphs also show that the removal percentage is higher in any region (above 90%), which may extend the application range of HRT, current, and coagulant.

Figs. 7–9 show the response surfaces for turbidity removal.

Figs. 7–9 show that the greatest removal of turbidity occurs approximately at the center point for HRT, coded value 1 for the concentration of coagulant and a wide range for electric current.

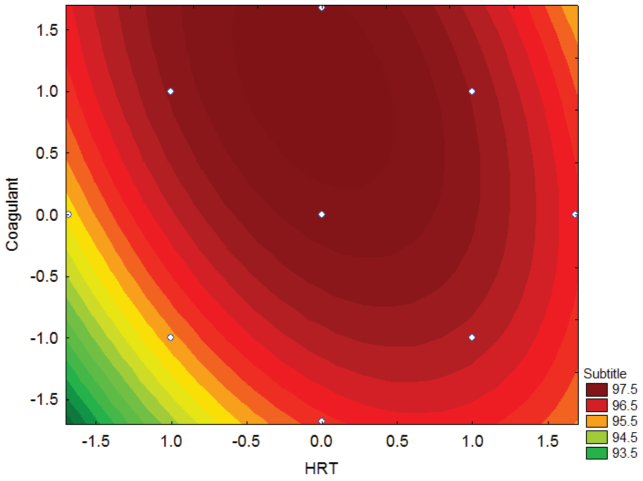

Fig. 4. Response surface for color removal (coagulant × HRT).

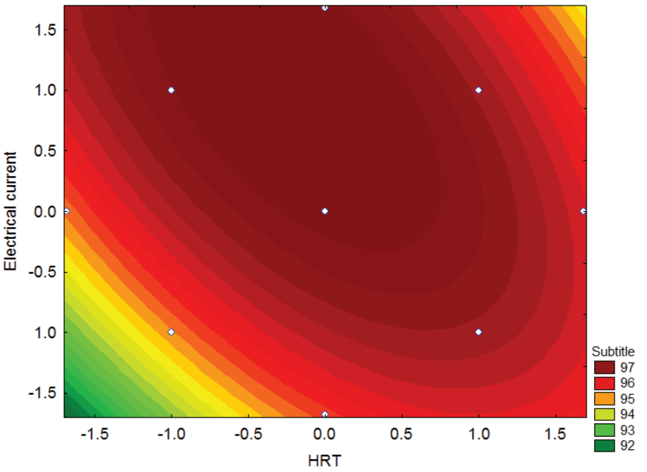

Fig. 5. Response surface for color removal (electrical current × HRT).

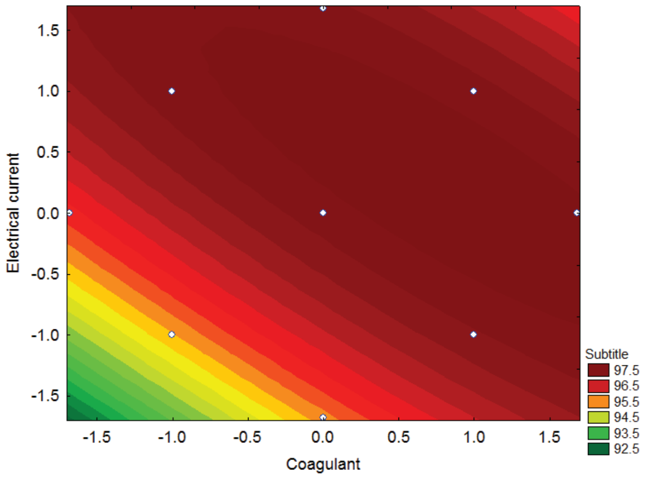

Fig. 6. Response surface for color removal (electrical current × coagulant).

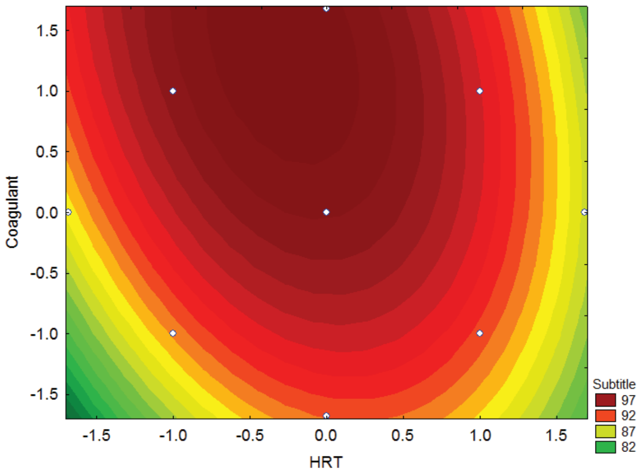

Fig. 7. Response surface for turbidity removal (coagulant × HRT).

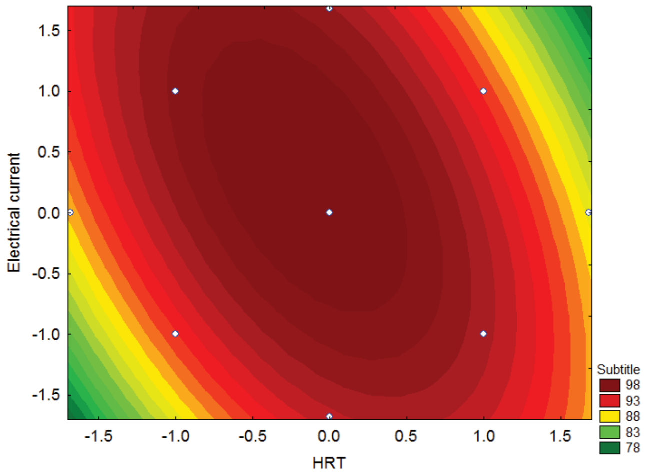

Fig. 8. Response surface for turbidity removal (electrical current × HRT).

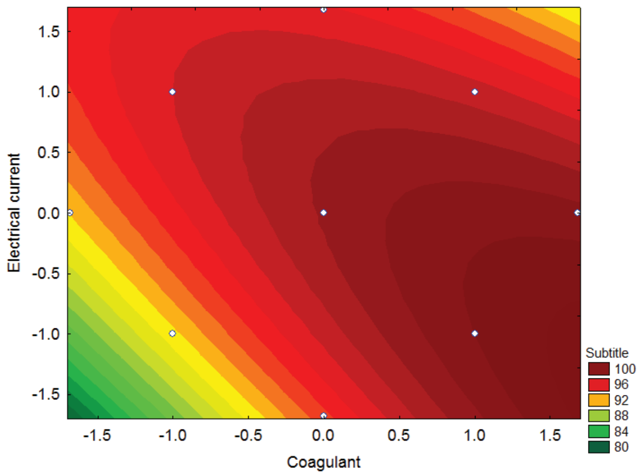

Fig. 9. Response surface for turbidity removal (electrical current × coagulant).

However, in case of color removal, the graphs show that the percentage of turbidity removal is higher in any region, which can extend the application ranges of HRT, current, and coagulant.

3.4. Overall desirability of the system

Fig. 10 shows the application of the methodology of Derringer and Suich [15] to optimize the EC process. Since only the response variables color and turbidity removal obtained valid models, the desirability was built with these two variables.

In Fig. 10, the overall desirability was 0.98141 and the optimized condition for HRT was the coded value 0, which corresponds to 10 min. For the tannin-based coagulant, the optimized condition was 0.672 for the coded value, which corresponds to 0.775 mL L^{-1}. For the electric current, the optimized condition was the coded value 0.336, which corresponds to 0.68 A, and a current density of 13.6 mA cm^{-2}.

The crucial factor to determine the optimal point is HRT followed by coagulant concentration, given the sharper inclinations in the graph. These inclinations are highly instructive because they provide the idea of room for maneuver around the optimum conditions [19].

The graph of the overall desirability according to the electrical current shows that this factor may vary within a reasonable range without compromising the desirability value. In contrast, any change to the HRT value will cause a sudden drop in desirability. Thus, this factor must be kept under strict control.

Fig. 11 shows the response surfaces for desirability, corroborating the information observed in Fig. 10.

3.5. Residual aluminum concentrations in the treated effluent

Table 13 shows the values found for aluminum in the treated effluent.

In Table 13, the aluminum values did not exceed 2.71 mg L^{-1}; they are considered low when compared with the values found in other works, where EC was only used with aluminum electrodes in the treatment.

Orssatto et al. [18], treating wastewater from a pig slaughterhouse and packing plant through EC, found aluminum residue varied from 15.254 to 54.291 mg L^{-1}. However, the study by Orssatto et al. [18] used a range of 10–30 V of electric potential difference and 10–30 min of HRT.

Pelegrino [20] states that tannin-based coagulants can adsorb metals dissolved in water and, when these metals coagulate, they precipitate and can be removed. This fact can justify the low concentrations of residual aluminum in the treated effluent.

3.6. Operating cost of treatment

The costs of the treatment were calculated using the values of electric energy consumption of aluminum, and organic coagulant, with Eqs. (2)–(5).

The costs were calculated only for the best condition found for the treatment by desirability, which was 10 min from the time of hydraulic retention, 0.775 mL L^{-1} for the organic coagulant and 0.68 A of electric current, corresponding to 20.88 V

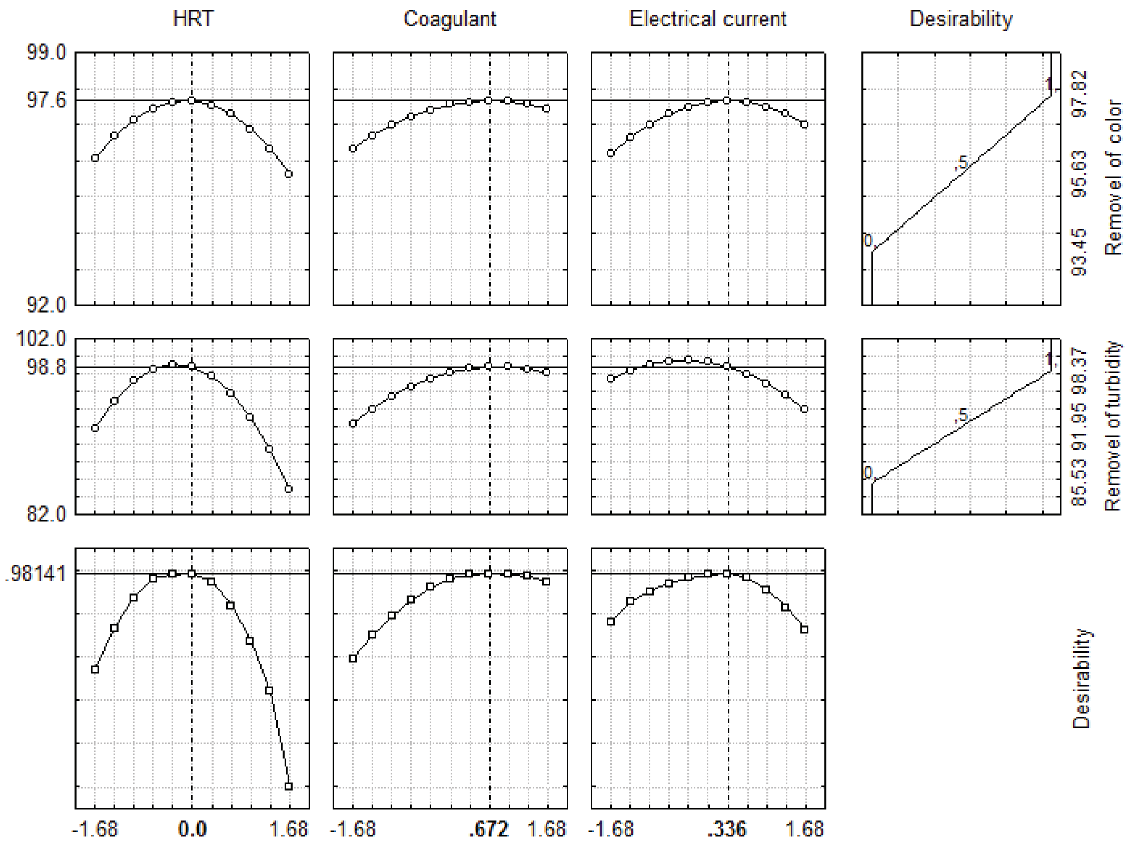

Fig. 10. Graphs of desirability.

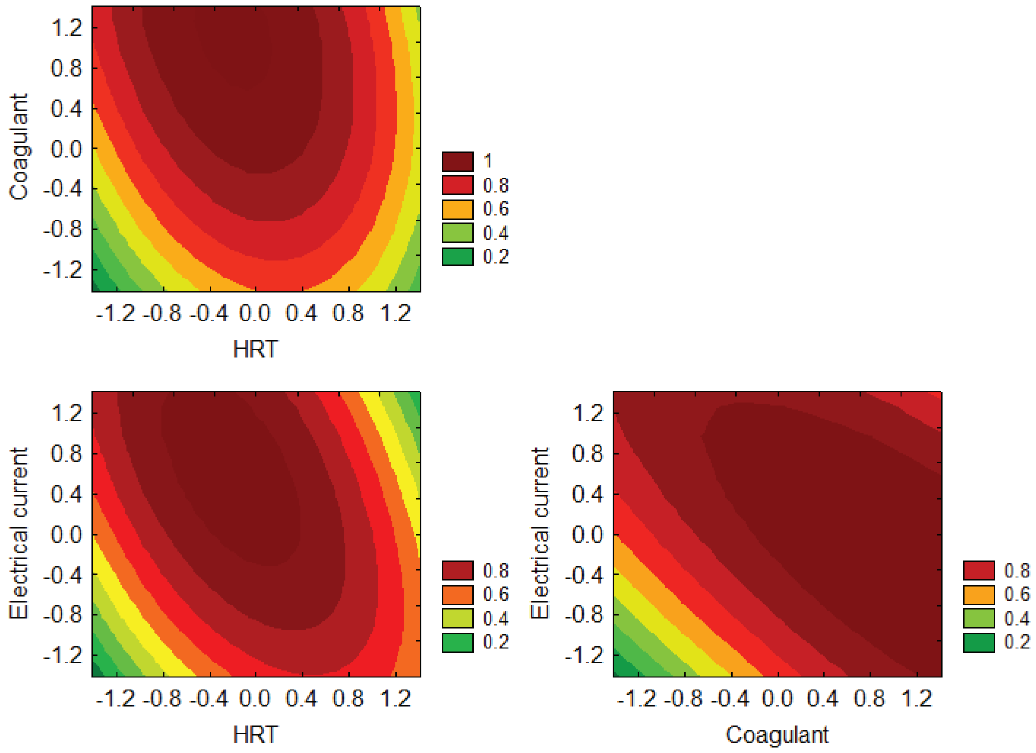

Fig. 11. Response surfaces for desirability.

Table 13
Residual aluminum values

Experiment	Value (mg L^{-1})
1	0.12 (±0.16)
2	0 (±0.0)
3	0 (±0.0)
4	0.03 (±0.04)
5	1.87 (±1.15)
6	2.71 (±0.84)
7	2.59 (±1.56)
8	2.62 (±1.04)
9	0.91 (±1.06)
10	1.23 (±0.26)
11	0.58 (±0.13)
12	0.66 (±0.13)
13	0 (±0.0)
14	1.54 (±0.58)
15	1.90 (±0.00)
16	1.02 (±1.44)
17	1.34 (±1.85)

for the electric potential difference, considering the electrical conductivity of the effluent.

When these values were applied to Eq. (2), the obtained value was 2.96 m^{-3} kWh of electrical energy, while, with Eq. (3), the obtained value was 0.0475 kg m^{-3} for aluminum consumption. When Eq. (4) was used, however, the value was 0.775 L m^{-3} of organic coagulant for the treatment.

The electricity and aluminum costs estimates were obtained from the US$ values used and provided by the electric power company of Paraná (COPEL) and the Brazilian Aluminum Association. According to COPEL [21], the cost per kWh for the plant is US$ 0.20 and the kilogram of aluminum, according to ABAL [22], is US$ 1.66. The cost of the coagulant is US$ 0.53 L^{-1}, according to the supplier.

Based on Eq. (5), the cost of treating the effluent from the pork packing plant in optimum conditions was approximately US$ 1.08 m^{-3}.

Asselin et al. [23] when treating wastewater from a slaughterhouse using EC, obtained an operating cost of US$ 0.71 m^{-3}. However, the authors used an electrical current of 0.3 A and considered the cost of electricity of US$ 0.06 kWh^{-1}.

Bayramoglu et al. [4] treated the effluents of a meat packing plant using EC and obtained a cost of USD 0.4 m^{-3}. Part of this difference in values is due to the addition of coagulant.

4. Conclusions

The EC technique, combined with organic coagulation to treat the effluents of a pig slaughterhouse and packing plant in a batch reactor, proved to be effective to remove turbidity, color, COD, and TKN. The results were as follows: 98.37% of maximum efficiency for turbidity, 97.82% for color, 64.73% for COD, and 65.57% to TKN.

Based on statistical analysis, they were obtained the mathematical models for the parameters of color and turbidity removal. The calculation of the desirability function showed that the optimum treatment conditions were 10 min for HRT, 0.774 mL L^{-1} concentration of tannin-based coagulant, 0.68 A for electrical current, and a current density of 13.6 mA cm^{-2}.

In the tests of the treated effluent, the concentration did not exceed 2.11 mg L^{-1} in the residual aluminum analysis, lower than the values found in literature.

Finally, each cubic meter (m^3) of wastewater treated by consumed 2.96 kWh of electric energy and 0.0475 kg of aluminums, at a cost of US$ 1.08 m^{-3}.

The combination of EC and coagulant based on tannin caused the reduction of the electric current applied and the time of the electrolysis, consequently there was a lower consumption of electric energy, representing an additional economic advantage of the system.

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