OPTIMIZATION OF A WASTEWATER TREATMENT SYSTEM COMPOSED BY ELECTROCHEMICAL REACTOR AND DISSOLVED AIR FLOTATION

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ABSTRACT

Using combined technologies to treat effluents can be an attractive option to achieve treatment efficiency associated with resource savings. Thus, this work aimed to evaluate the performance of electrocoagulation in a cylindrical batch reactor followed by dissolved air flotation in effluent treatment from a slaughterhouse. Through two Central Composite Rotational Design (CCRD), it was possible to evaluate the effects of electrolysis time and electric current density for the electrocoagulation stage and the saturation pressure and hydraulic retention time for the dissolved air flotation stage. The results obtained from the tests carried out indicate that the proposed treatment system was promising for removing COD (81.13%), turbidity (96.84%), and color (95.48%). With the association of the two technologies, it was possible to operate in milder conditions, which provided a low energy consumption for the electrochemical treatment stage. The optimized conditions for the electrocoagulation step provided energy consumption of 333.76 ± 0.515 Wh.m^{-3}, a low and attractive value.

KEYWORDS: *Association of technologies, Process optimization, Physical-chemical treatment of effluents, Wastewater treatment.*

I. INTRODUCTION

The animal slaughter sector produces a large volume of wastewater due to cleaning processes, animal slaughter, and industrial meat processing, and this sector is part of large industries in several countries around the world [1]. Cleaning operations are responsible for the high consumption of water in slaughterhouses, which are used for washing trucks, floors, industrial areas, washing carcasses, viscera, and intestines; handling of by-products and waste; cleaning and sterilization of machinery and equipment, walls, and countertops, steam generation, and compressor cooling [2]. The water consumed in carcass cleaning and washing operations corresponds to an average of 1093 to 1125 liters per slaughtered animal [3].

The characteristics of wastewater generated in pork slaughterhouses are complex, and effluent treatment is necessary to prevent the release of these pollutants directly into the environment [4,5]. The main contaminants present in this effluent are blood, fat, suspended solids, fatty acids, proteins, nitrogen from organic matter, fecal coliforms, and phosphorus [6].

The conventional methods for treating effluent from slaughterhouses and pork slaughterhouses include anaerobic and aerobic lagoons, anaerobic reactors, coagulation/flocculation, and aerobic granulation

[7]. However, when these effluents have a low content of colloidal particles suspended in organic matter, these processes are inefficient.

In Brazil, traditionally, effluent treatment from pork slaughterhouses and slaughterhouses is carried out by biological processes, in stabilization and aerated lagoons, due to the climatic factors of the region. When ponds are well designed, they have good removal of organic matter but occupy large areas, generating bad odors and discomfort in the surroundings [8].

Thus, a proposal for treating wastewater generated in slaughterhouses and pork slaughterhouses is through electrocoagulation. This technique connects electrodes immersed in the effluent to a direct current source. Thus, the electric current passes through the positive and negative electrodes, resulting in reduction and oxidation reactions, which result in coagulant compounds responsible for forming flocs from the suspended solids in the effluent.

Another important technology for treating effluents from slaughterhouses and pork slaughterhouses is dissolved air flotation (DAF), a process applied to remove a wide variety of suspended solids (turbidity, algae, oils, fatty and precipitates, etc.). The removal of suspended solids occurs using small air bubbles formed from depressurizing a stream of water saturated with air at high pressures. Thus, the generated microbubbles are responsible for removing the suspended material dispersed in a liquid phase [9].

Given this, the main contribution of this work was the application of electrocoagulation followed by dissolved air flotation (DAF) in the treatment of effluents from slaughterhouses and pork slaughterhouses. This process can work in milder conditions, reducing the cost of the process without losing the quality of the applied treatment. In addition, using both technologies has the advantage of not using chemical products, less occupation of available area, and the non-generation of bad odors in comparison to traditional treatments carried out by ponds.

This paper is organized as follows: Section II presents essential information about the wastewater, the object of the application and details the entire proposed treatment system (electrochemical reactor and FAD). Also, this section contains the experimental planning strategy employed, as well as the optimization criteria. Section III presents the main results of the association of the two technologies, and the optimized operational conditions are shown. A comparison is made with literature data based on treatment performance and energy consumption. In section IV, the final considerations are presented.

II. MATERIALS AND METHODS

The effluent used in the research was collected in a slaughterhouse and pork slaughterhouse located in the southern region of Brazil. This industry slaughters 6,900 animals daily and has a flow of approximately 5,280 m³ of effluent/day. The effluent treatment plant comprises sieves, decanters, a grease trap, a primary physical-chemical floater, an equalization pond, two anaerobic ponds in sequence, an aerated pond, a decantation pond, and a tertiary physical-chemical floater. The company's treatment system has a division between the red and green lines. In the green line, liquid effluents that do not contain blood are destined. The red line is constituted by the effluents that contain blood. Both lines contain identical preliminary treatment systems comprising rotating screens and Parshall troughs. The two lines join in the sequence, and the effluent goes to a primary physical-chemical floater and an equalization pond.

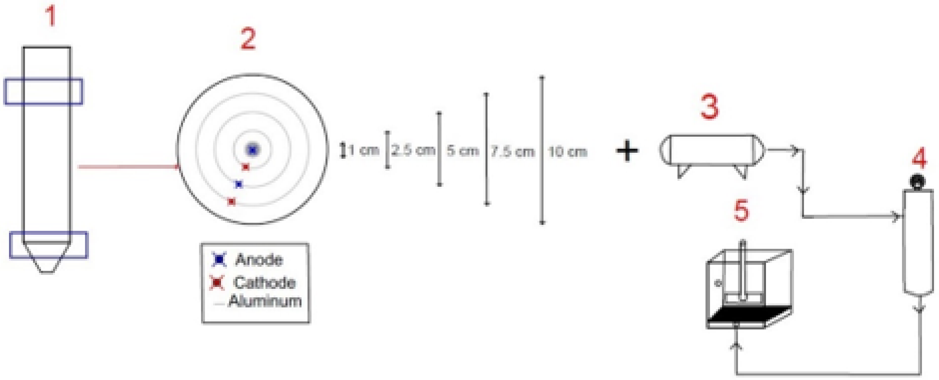
The effluent used for the electrocoagulation and dissolved air flotation tests was collected at the end of the primary treatment in an equalization pond, being stored in plastic gallons with a volume of approximately 5 L for 2 hours, obtaining the final amount of 50 L. The effluent from the swine slaughterhouse and slaughterhouse was characterized according to the following physical-chemical parameters: COD (Colorimetric), Turbidity (Nephelometric), Apparent Color (Spectrometry), pH (Potentiometric), Electrical Conductivity (Conductivity meter) and aluminum residual (Plasma Optical Emission Spectrometry).

Aiming to treat the effluent from the swine slaughterhouse and slaughterhouse, an electrochemical reactor was built in which the sacrificial electrodes were arranged as concentric tubes. The reactor consists of a 100 mm in diameter and 50 cm long PVC tube, another three concentric aluminum tubes of 75 mm, 50 mm, and 25 mm, respectively, and a solid aluminum cylinder with 10 mm in diameter.

All aluminum structures act as sacrificial electrodes. In the upper part of the reactor, four aluminum metallic rods were welded to connect the power supply to the electrodes.

The reactor was charged with 4 L of untreated effluent for each test. Due to the generation characteristics of this effluent, it had sufficient electrical conductivity to enable electrochemical treatment. Therefore, no adjustments were made to the conductivity or the pH. Afterward, electrocoagulation was carried out under electric current density and electrolysis time conditions as defined in the experimental design matrix. The effluent was previously fed to the reactor from the top for each batch. At the end of the electrolysis time, the treated effluent was discharged by gravity at the bottom of the reactor.

Next, the effluent treated by electrocoagulation is pressurized in a closed cylindrical saturation chamber connected to a compressor. After reaching the desired pressure, the depressurization stage begins, enabling Dissolved Air Flotation and complementing the effluent treatment from the electrocoagulation stage (Figure 1).



1 – Electrochemical Reactor;
2 – Electrochemical Reactor (top view detail);
3 – Compressor connected to saturation chamber;
4 – Saturation Chamber;
5 – Rectangular bowl adapted to perforated plate.

Figure 1. Electrocoagulation followed by a Dissolved Air Flotation system

The equipment used to conduct the tests with dissolved air flotation comprises a saturation chamber connected to an air compressor. The chamber was built with stainless steel material, with a wall thickness of 1 mm, a circular cross-section with a diameter of 125 mm, an internal volume of approximately 12.2 L, and a height of 1 m. The equipment is estimated to have a maximum operating pressure of 800 KPa. A specific metallic structure suspends the camera to facilitate the agitation and homogenization process during the tests with the effluent samples. A jar test connected to the saturation chamber by a hose was also adapted to depressurize the effluent and promote flotation.

2.1. Experimental design

Two CCRD (Central Composite Rotational Design) were performed as an experimental planning strategy, one for each treatment step (Electrocoagulation and Dissolved Air Flotation). The test matrices were independent of each other. For the electrocoagulation step, a CCRD was performed with 2^2 factorial trials, including four axial points and three repetitions at the central point, totaling 11 trials (Table 1). The tests of the electrocoagulation stage were carried out with untreated effluent. The response variables to verify the efficiency of the treatment of the effluent under study were the average color removal, chemical oxygen demand (COD), and turbidity, in addition to the residual aluminum concentration and electrical energy consumption.

Table 1. Matrix of the experimental design of the coded and real values used in the CCRD in the electrocoagulation tests.

Tests	Coded electric current density (X1)	Electric current density($mA.cm^{-2}$)	Coded electrolysis time (X2)	Electrolysis time (min)
1	+1	9	-1	6.45
2	-1	4	-1	6.45
3	+1	9	+1	13.55
4	-1	4	+1	13.55
5	-1.41	3	0	10
6	+1.41	10	0	10
7	0	6.5	-1.41	5
8	0	6.5	+1.41	15
9	0	6.5	0	10
10	0	6.5	0	10
11	0	6.5	0	10

In the Dissolved Air Flotation stage, the CCRD (Central Composite Rotational Design) was carried out with two independent variables (hydraulic retention time and saturation pressure) with 2^2 factorial tests including four axial points and four repetitions in the central point, totaling 12 tests (Table 2). After electrochemical treatment, the dissolved air flotation stage tests were carried out with effluent. For this purpose, after establishing the best condition of electric current density and electrolysis time, the volume of effluent required by the DAF design matrix underwent electrocoagulation, with the treated effluent being homogenized and stored under freezing and then directed to the DAF. The response variables to verify the efficiency of the effluent treatment under study were the average removal of color, chemical oxygen demand (COD), and turbidity.

Table 2. Experimental design matrix of coded and real values used in CCRD in Dissolved air flotation tests.

Tests	Coded pressure (X1)	Pressure (Psi)	Coded hydraulic detention time (X2)	Hydraulic retention time (min)
1	-1	22.3	-1	8.9
2	+1	57.7	-1	8.9
3	-1	22.3	+1	13.1
4	+1	57.7	+1	13.1
5	0	40	0	11
6	0	40	0	11
7	0	40	0	11
8	0	40	0	11
9	-1.41	15	0	11
10	+1.41	65	0	11
11	0	40	-1.41	8
12	0	40	+1.41	14

Based on the results obtained with the execution of the experimental design, through analysis of variance (ANOVA), the effects of the factors on the response variables are evaluated. The quadratic models (one for each response) are also adjusted to base the optimization of the operational conditions of the two treatment steps. In this way, conditions are sought that maximize responses related to treatment efficiency (percentage removals of COD, color, and turbidity). However, concomitantly the minimization of other responses, such as energy consumption and residual aluminum concentration, in the electrocoagulation step.

2.2. Energy consumption of the electrocoagulation stage

For the treatment system proposed in this work, electricity consumption is calculated based on the electricity consumed per treated effluent volume (KWh.m^{-3}). Equation 1, described by [10], calculates electricity consumption.

$$CE = \frac{(V.i.t)}{Vol} \tag{1}$$

Where:

EC: Electricity consumption (KWh.m^{-3});

V: Potential difference (V);

i= Intensity of electric current (A);

t= Electrolysis time (min);

Vol= Volume of treated effluent (m^3).

2.3. Global optimization

With a holistic view of the proposed effluent treatment system, a set of operating conditions is sought that provides the best performance for each stage (electrocoagulation and DAF), each with its multiple responses. It is, therefore, necessary to carry out the global optimization of each stage of the treatment.

For this purpose, the desirability function [11] was applied, presented in Equations 2, 3, and 4. This method seeks to evaluate the sets of responses to determine the most appropriate conditions for the studied variables. Then, the desirability function varies according to each response obtained with acceptable values to reach a more desirable point. Optimization is achieved by maximizing this function, which considers all response variables with statistically valid models.

In this way, the maximization of the Desirability Function "D" (Equation 2) is sought, which can vary in the interval [0,1].

$$D = \sqrt[m]{d_1 d_2 \dots d_m} \tag{2}$$

Where "di" represent the individual desirability, "m" being the number of these.

When one wants to maximize the individual desirability di(Yi), Equation 3 is used:

$$di(yi(x)) = \begin{cases} 0 \ \ se\, Yi\,(x) < Li \\ \left[\dfrac{(Yi(x) - Li)}{(Ui - Li)}\right]^s \ se\, Li \le Yi\,(x) \le Ui \\ 1 \ \ se\, Yi\,(x) > Ui \end{cases} \tag{3}$$

Ui and Li correspond to the highest and lowest acceptable value for the Yi response, respectively. "s" is a value called "weight", defined by the analyst to determine how important it is for Yi to be close to the maximum.

When one wants to minimize the individual desirability di(Yi), Equation 4 is used:

$$di(yi(x)) = \begin{cases} 1 \ \ se\, Yi\,(x) < Li \\ \left[\dfrac{(Ui - Yi(x))}{(Ui - Li)}\right]^t \ se\, Li \le Yi\,(x) \le Ui \\ 0 \ \ se\, Yi\,(x) > Ui \end{cases} \tag{4}$$

Where "t" is the weight to determine how important it is for Yi to be close to the minimum.

III. RESULTS AND DISCUSSION

Table 3 shows the mean values of the physical-chemical parameters and results of the effluent characterization from the swine slaughterhouse and slaughterhouse before treatment used in the present study. It can be verified that the COD and turbidity values were mainly high compared to other studies found in the literature. There is also a discrepancy between the values reported in the literature, possibly due to the different treatment stages before the collection points.

Table 3. Characterization of effluent from pork slaughterhouses and slaughterhouses

Reference	Turbidity (UNT)	Electric conductivity (mS.cm^{-1})	Color (UC)	pH	(COD) (mg.L^{-1})
Present work	2,462 ± 220.33	3.21± 0.04	3,192.8± 95.36	6.39± 0.01	13,452.5± 224.6
[12]	-	-	-	-	6,057 ± 172.6
[13]	-	9.14 ± 1.51	-	7.31 ± 0.12	5,817 ± 473
[14]	434	-	5,000	8.71	2,185
[8]	380	3.91	2,790	7.13	2,402.5
[15]	156	-	1,120	7.84	970
[16]	380	2.92	2,790	7.13	2,402
[17]	-	-	-	6.9 ± 0.13	4,326.3 ±1,163.4

3.1. Optimization of the electrocoagulation step

Table 4 presents the results obtained with the execution of the test matrix of the experimental design in the electrocoagulation stage. Notably, the removal percentages varied between 74.50% and 87.80% for COD, 76.05% and 94.98% for apparent color, and 81.40% and 94.98% for turbidity. Furthermore, energy consumption ranged from 447.20 to 2060.97 Wh.m^{-3}, and residual aluminum concentration ranged from 12.8 to 34.2 mg.L^{-1}. In many works, the focus is only on the treatment system's performance. Thus, high levels of removal of organic matter, suspended and dissolved solids are achieved; however, there is high energy consumption.

In the study carried out by [16], the effluent from the slaughterhouse and pork slaughterhouse was subjected to an electrochemical treatment with a continuous flow reactor, controlling the applied potential difference and the hydrolysis time and evaluating the removal of color, turbidity, and COD, finding maximum removals of 91.76, 74.45 and 61.07% respectively, in the condition of 0.47 to 1.5 A and from 10 to 30 minutes.

[18] carried out a study of electrocoagulation using refrigerator effluent. They found the removal of 94% for color, 98% for turbidity, and 87% for COD operating with an electric current of 4 A, for 52min and 30s and pH from the effluent from 5. [19] conducted a study of electrocoagulation in a pig slaughterhouse with an electrolysis time of 30 min and an electric current density of 130 mA.cm^{-2}, obtaining the removal of 97.3% of COD.

Table 4. Results of COD, color and turbidity removal efficiency, and values of energy consumption and residual food concentration performed in electrocoagulation tests

Tests	Turbidity Removal (%)	Color Removal (%)	COD Removal (%)	Total energy consumption (Wh.m^{-3})	Residual concentration of aluminum (mg.L^{-1})
1	86.71	76.05	80.20	1,012.10	26.2
2	92,.50	87.33	82.70	447.20	21.6
3	90.10	94.91	81.88	2,060.97	18.6
4	98.86	91.49	85.70	946.68	15.8
5	81.40	90.93	83.40	545.97	16.4
6	95.20	94.73	87.80	1,758.40	12.8
7	90.38	80.34	74.50	523.48	14.6
8	96.50	94.98	81.48	1,547.68	13.2
9	96.20	91.73	81.65	1,024.20	34.2

10	94.72	90.97	81.47	1,031.79	26.2
11	90.47	91.01	80.58	1,009.03	25.8

Thus, from the data obtained, it can be verified that the energy consumption varies according to the operational conditions adopted for carrying out each test of the electrocoagulation treatment. This variable must be considered in the optimization since minimizing energy consumption per cubic meter of treated effluent is extremely important for the economic and environmental viability of the process. Studies in the literature also include energy consumption among the factors considered.

[20], when carrying out a study of anaerobic post-treatment in a slaughterhouse and pork slaughterhouse by electrocoagulation, obtained an energy consumption range of 820.31 to 5262.50 $Wh.m^{-3}$ operating with a potential difference range of 0.30 to 0.73 V and electrolysis time of 10 to 20 minutes.

[21], on the other hand, when applying electrocoagulation-flotation in wastewater treatment from a swine slaughterhouse in a potential difference range of 5.6 V, electrolysis time of 1 hour with a volume of 3.5 L, obtained an energy consumption of 4800 $Wh.m^{-3}$. [8], when performing effluent treatment from a pork slaughterhouse and slaughterhouse with a potential difference of 20 V and electrolysis time of 20 minutes, obtained an electrical energy consumption of 10750 $Wh.m^{-3}$.

The residual presence of aluminum in the treated effluent from the electrocoagulation stage can be considered an unfavorable factor due to the high polluting potential and aluminum toxicity in water bodies and soil.

In a study by [21], 9.52 $mg.L^{-1}$ of aluminum was found in treating wastewater from a swine slaughterhouse. [8], when carrying out a study of the application of electrocoagulation in the treatment of effluent from a pork slaughterhouse and slaughterhouse, it found a residual concentration of aluminum that ranged from 15.254 to 54.291 $mg. L^{-1}$ operates in a range of 10 to 30 V and an electrolysis time of 10 to 30 minutes.

Analyzing the results obtained in the tests made it possible to adjust the mathematical models for the response variables of the removal of turbidity, color and COD, energy consumption, and residual aluminum concentration and verify the statistical validity. Table 5 shows all the terms of the adjusted quadratic models. Terms are considered significant, at 95% confidence, when they have a p-value < 0.05.

Table 5. The regression coefficient for the removal of response variables

Parameters	Variable	Coefficient	Standard error	t calculated	p-value
COD Removal (%)	Mean	111.93	25.05	5.011	0.000
	X1	0.001	0.001	0.0003	0.986
	$X1^2$	32.39	32.39	6.463	0.051
	X2	26.43	26.43	5.275	0.070
	$X2^2$	11.34	11.34	2.263	0.192
	X1.X2	0.435	0.4356	0.0869	0.779
Color Removal (%)	Mean	371.5	38.39	7.676	0.000
	X1	0.784	0.784	0.1021	0.762
	$X1^2$	0.048	0.048	0.006	0.939
	X2	239.0	239.0	31.12	*0.002
	$X2^2$	35.21	35.21	4.585	0.085
	X1.X2	38.39	54.02	7.034	*0.045
Turbidity Removal (%)	Mean	252.1	166.0	33.21	0.000
	X1	3.020	3.020	0.090	0.775
	$X1^2$	34.26	34.26	1.031	0.356
	X2	42.35	42.35	1.275	0.310

	$X2^2$	0.070	0.070	0.002	0.965
	X1.X2	2.205	2.205	0.066	0.806
Total energy consumption (Wh.m^{-3})	Mean	2669	2629	526	0.000
	X1	1439	1439	2737	*0.000
	$X1^2$	2851	2851	54,24	*0.000
	X2	1122	1122	2135	*0.000
	$X2^2$	903	903	1.718	0.246
	X1.X2	7537	7537	143.3	*0.000
Residual concentration of aluminum (mg.L^{-1})	Mean	471.8	161.7	32.34	0.000
	X1	0.677	0.677	0.020	0.890
	$X1^2$	168.8	168.8	5.219	0.071
	X2	29.63	29.63	0.916	0.387
	$X2^2$	191.1	191.1	5.910	0.059
	X1.X2	0.810	0.810	0.025	0.880

X1-Coded electrical current density (mA.cm^{-2}); X2-Coded electrolysis time (min);
* Significant terms with p-value < 0.05

Table 6 presents the reparametrized mathematical models. Terms that were not significant at 95% confidence were excluded from the models, and their contributions were incorporated into the residuals.

Table 7 shows that the F calculated for the regression is highly significant for color and COD removal, energy consumption, and residual aluminum concentration. As the models had a p-value less than 0.05 and the Fcal>Ftab for color removal and COD, energy consumption, and residual aluminum concentration, it can be concluded that the models that fit the experiment data are valid. As for the removal of turbidity, the generated model is not valid since Fcal<Ftab and p-value > 0.05.

Table 6. The regression coefficient for the removal of response variables (reparametrized models)

Parameters	**Variable**	**Coefficient**	**Standard Error**	**t calculated**	**p-value**
COD Removal (%)	Mean	79.89	0.9023	84.54	0,000
	$X1^2$	2.819	1.734	3.250	*0.001
	X2	1.820	1.519	2.396	*0.043
Color Removal (%)	Mean	91.33	0.995	91.75	0.000
	X2	5.474	1.676	6.530	*0.000
	$X2^2$	-2.534	1.913	-2.648	*0.033
	X1.X2	3.675	2.367	3.104	*0.017
Total energy consumption (Wh.m^{-3})	Mean	1033.00	10.20	101.30	0.000
	X1	424.8	17.18	49.45	*0.000
	$X1^2$	67.64	19.61	6.899	*0.000
	X2	375.21	17.18	43.67	*0.000
	X1.X2	137.2	24.26	11.31	*0.000
Residual concentration of aluminum (mg.L^{-1})	Mean	28,70	2,834	10,12	0,000
	$X1^2$	-5,490	4,148	-2,646	*0,029
	$X2^2$	-5,842	4,148	-2,816	*0,022

X1-Coded electrical current density (mA.cm^{-2}); X2-Coded electrolysis time (min);
* Significant terms with p-value < 0.05

Table 7. Analysis of variance of response variables

Parameters	**Source of variation**	**SS**	**DF**	**Fcal**	**Ftab**	**p-value**
Turbidity Removal (%)	Regression	81.91	5	0.592	4.387	0.709
	Residuals	166.07	6			
	Total	247.98	11			
COD Removal (%)	Regression	75.09	2	9.173	4.256	0.007
	Residuals	36.84	9			
	Total	111.93	11			
Color Removal (%)	Regression	332.3	3	22.590	4.066	0.0003
	Residuals	39.23	8			
	Total	371.53	11			
Total energy consumption ($Wh.m^{-3}$)	Regression	2665768.7	4	1320.8	4.120	3.78×10^{-10}
	Residuals	3531.9	7			
	Total	2669.30	11			
Residual concentration of aluminum ($mg.L^{-1}$)	Regression	360.03	2	8.401	4.256	0.009
	Residuals	192.84	9			
	Total	552.88	11			

SS= Square Sum; DF= Degree of Freedom; Fcal= F calculated; Ftab= F tabulated.
*Significant terms with p-value or < 0.05.

Thus, the adjusted models for the response variables of COD, color, energy consumption, and residual aluminum concentration are presented in Equations 4, 5, 6, and 7.

$$\boldsymbol{COD\ Removal}\ (\%) = \boldsymbol{79{,}89 + 1{,}820\, X_2 + 2{,}819\, X_1^2} \tag{4}$$

$$Color\ Removal\ (\%) = 91{,}33 + 5{,}474\, X_2 - 2{,}534\, X_2^2 + 3{,}675\ X_1 . X_2 \tag{5}$$

$$Total\ energy\ consumption\ (Wh.m^{-3}) \tag{6}$$

$$= 1033 + 424{,}8\, X_1 + 67{,}64\, X_1^2 + 375{,}21\, X_2 + 137{,}2\, X_1 . X_2$$

$$Residual\ concentration\ of\ aluminum\ (mg.L^{-1}) = 28{,}70 - 5{,}490\, X_1^2 - 5{,}842\, X_2^2 \tag{7}$$

The graphical representations of the mathematical models for color removal and COD, energy consumption, and residual aluminum concentration are illustrated in Figure 2.

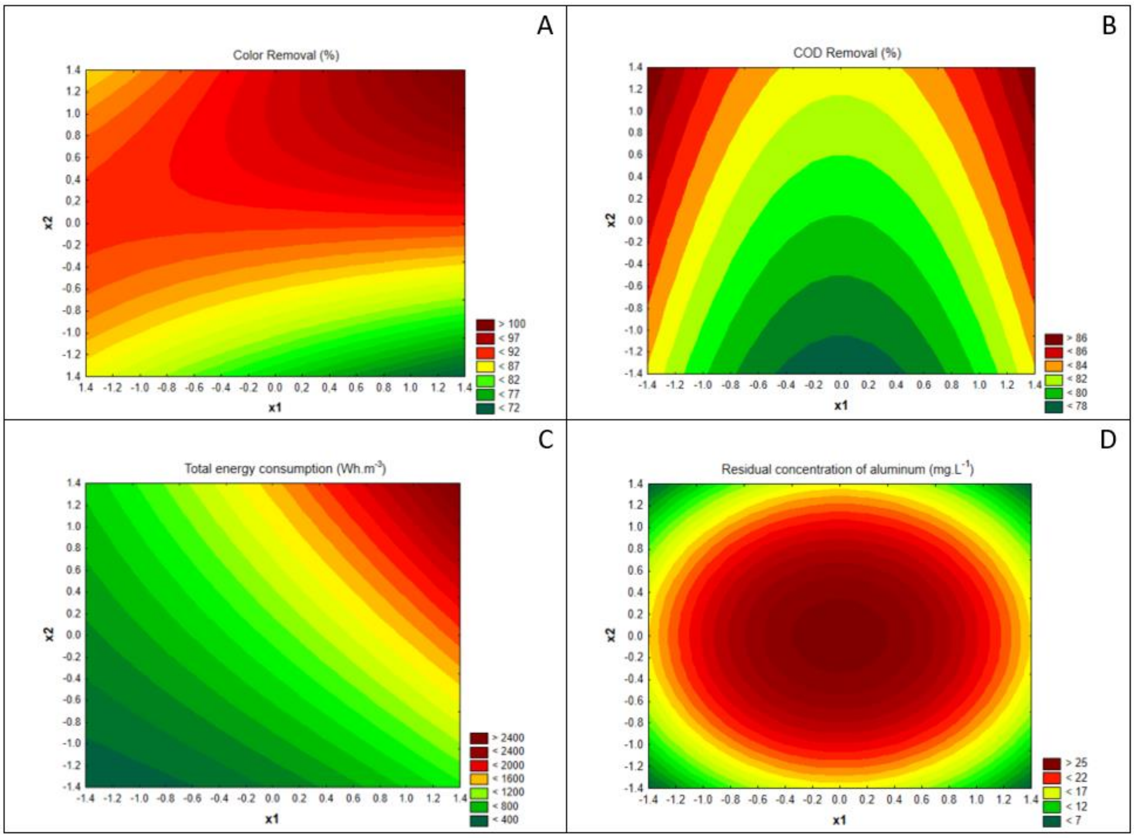


Figure 2. Contour plots for the response variables: (A) Color Removal, (B) COD Removal, (C) Total Energy consumption, and (D) Residual concentration of aluminum.

We can conclude in Figure 2 in item A that the highest apparent color removal values can be obtained by increasing the applied current and electrolysis time. Furthermore, the area with the best color removal indicators is within the range of 9.73 to 10 mA.cm^{-2} for the electric current density and electrolysis time of 12.84 to 14.96 minutes. For COD, we can observe in item B that the region with the highest removal percentage is 9.48 to 10 mA.cm^{-2} for the electric current density and electrolysis time of 14.25 to 14.96 minutes.

Regarding energy consumption, as expected, we can observe smaller energy consumption ranges obtained in item C as the applied electric current and electrolysis time decrease. In addition, the region with the lowest energy consumption range is 3.03 to 5.02 mA.cm^{-2} for the electric current density and electrolysis time of 5.04 to 6.81 minutes. As for the residual aluminum concentration, we can observe in item D that the smallest ranges are obtained as the applied electric current and electrolysis time decrease. In addition, the region with the smallest residual aluminum concentration range is 3.03 to 3.28 mA.cm^{-2} for the electric current density and electrolysis time of 5.04 to 5.40 minutes.

3.2. Global optimization and experimental validation for the electrocoagulation step

The desirability function was maximized for the electrocoagulation step. For this purpose, statistically valid and reparametrized models were considered. Thus, the analysis indicated that the optimal operating conditions for the electrocoagulation step were: an electric current density of 3 mA.cm^{-2} (x1 = -1.41) and an electrolysis time of 10 min (x2 = -1, 41).

Five validation tests were performed under these conditions after determining the optimal electric current density and electrolysis time values. In Table 8, it is possible to compare the predicted value obtained in the statistically valid models with the validation tests in the electrocoagulation stage about their mean percentage error.

Table 8. Results of experimental validation for the electrocoagulation step

Parameter	Real Value	Model predicted value	Percentage Error
COD Removal (%)	84.05 ± 0,287	82.93	1.34%
Color Removal (%)	93.55 ± 0,344	85.88	8.20%
Total energy consumption (Wh.m^{-3})	333.76 ± 0.515	312.84	6.27%

We can observe in the results that the optimal validation conditions for the parameters had a proximity between the values predicted by the mathematical models and those observed experimentally, which characterized an average percentage error of less than 10%.

3.3. Optimization of the Dissolved Air Flotation step

After the effluent treatment stage by electrocoagulation, the tests of the experimental design matrix for the DAF stage were carried out. The results of the average color, turbidity, and COD removal efficiency obtained in the dissolved air flotation tests are presented in Table 9. Such removal percentages refer to the conditions of the previously electrochemically treated effluent. Therefore, the initial values of the physical-chemical levels were already low compared to those found for the effluent without any treatment. Notably, the removal percentages varied between 23.08% and 37.26% for COD, 28.43% and 57.86% for apparent color, and 5.5% and 65.12% for turbidity.

The results obtained in the dissolved air flotation tests made it possible to evaluate whether the mathematical models adjusted for turbidity, color, and COD removal are valid. It can be seen (Table 10) that no term was significant (p-value>0.05) for the response variables of color removal, turbidity, and COD. It indicates no significant impacts on parameters indicative of treatment efficiency for the ranges of values studied for saturation pressure and HRT.

Table 9. COD, color, and turbidity removal efficiency performed in the Dissolved Air Flotation tests after being treated under optimal conditions by electrocoagulation

Tests	Turbidity Removal (%)	Color Removal (%)	COD Removal (%)
1	37.38	30.61	30.04
2	39.36	28.85	28.73
3	23.17	38.94	24.80
4	5.52	28.43	23.08
5	48.83	46.76	28.50
6	43.13	56.10	24.48
7	33.26	47.60	37.26
8	65.12	49.96	26.46
9	21.00	34.74	36.29
10	62.63	57.86	24.77
11	53.08	33.14	29.53
12	53.23	42.05	33.58

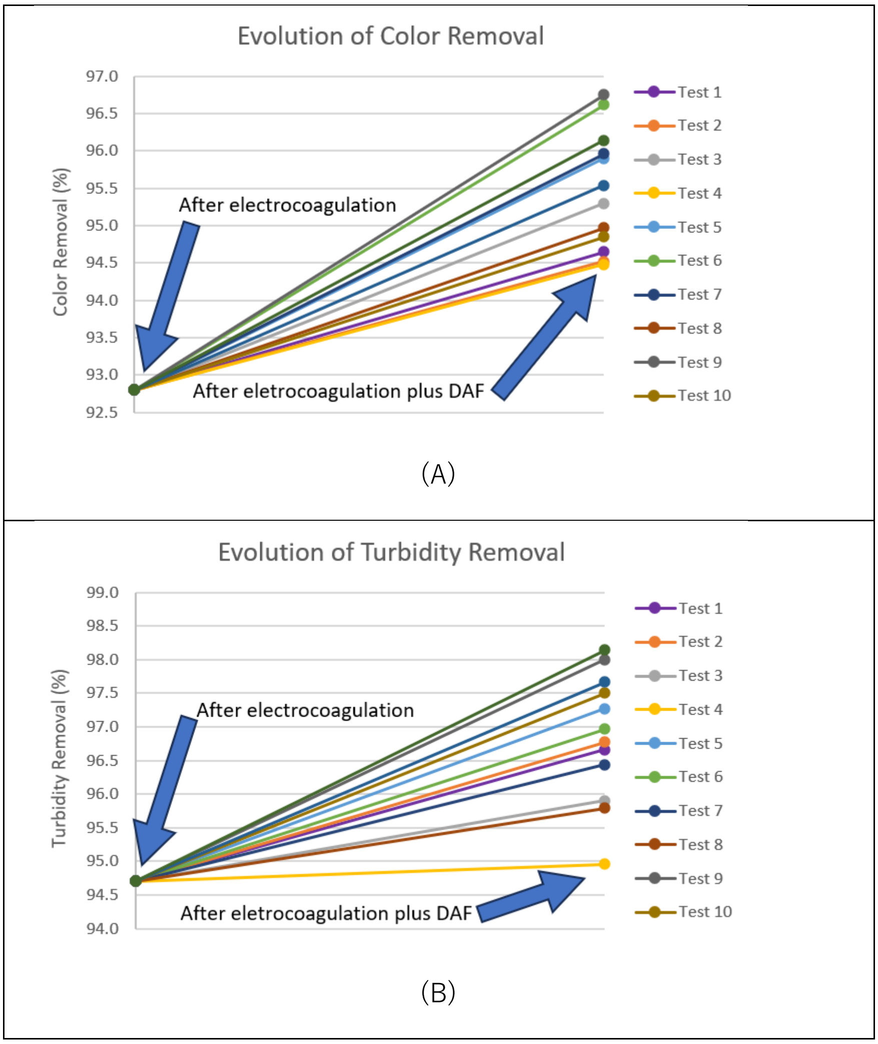
Table 10. The regression coefficient for the removal of response variables (DAF step)

Parameters	Variable	Coefficient	Standard Error	t calculated	p-value
COD Removal (%)	Mean	29.18	2.814	10.36	0.000
	X1	-2.417	3.986	-1.212	0.270
	$X1^2$	-0.430	4.469	-0.192	0.853
	X2	-0.648	3.986	-0.325	0.755
	$X2^2$	-0.086	4.469	0.038	0.970
	X1.X2	-0.102	5.629	0.036	0.972
Color Removal	Mean	50.13	4.636	10.81	0.000

(%)	X1	2.549	6.566	0.776	0.467
	$X1^2$	-4.492	7.361	-1.220	0.268
	X2	2.567	6.566	0.464	0.464
	$X2^2$	-8.870	7.361	0.052	0.052
	X1.X2	-2.186	9.273	0.653	0.653
Turbidity Removal (%)	Mean	47.64	10.25	4.644	0.003
	X1	5.395	14.53	0.742	0.485
	$X1^2$	-8.437	16.28	-1.035	0.340
	X2	-5.468	14.53	-0.752	0.480
	$X2^2$	-1,980	16,28	-0,243	0,816
	X1.X2	-4,906	20,51	-0,478	0,649

X1-Saturation Pressure (Psi); X2-Hydraulic retention time (min);
* Significant terms with p-value < 0.05.

Considering that the factors studied for the DAF stage (saturation pressure and HRT) did not have a significant effect on treatment performance, and also, considering that there was an increase in COD, color, and turbidity removals, these variables could be set at their minimum tested values. Figure 3 shows the evolution of the effluent treatment, considering the electrocoagulation step under optimal operational conditions and later the DAF for the 12 tests of the experimental planning matrix.



(A)

(B)

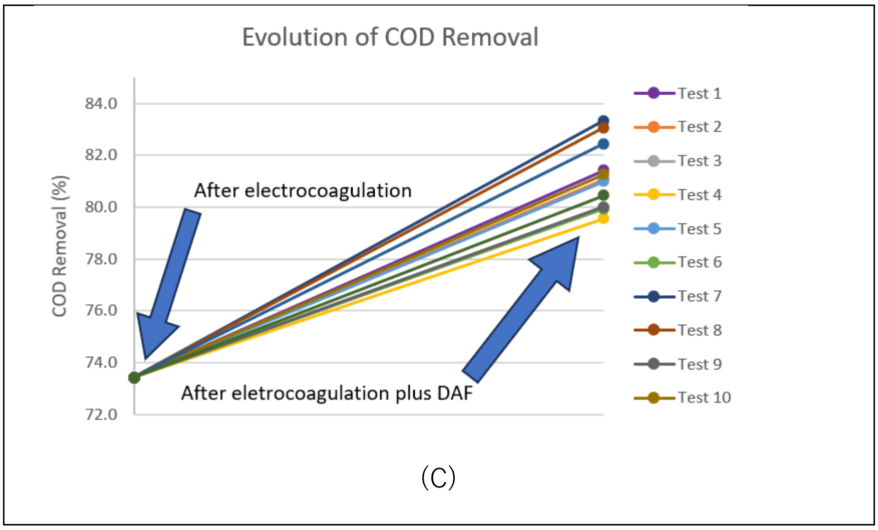


Figure 3. Evolution of effluent treatment: (A) Color Removal, (B) Turbidity Removal, (C) COD Removal.

Analyzing Figure 3, it is possible to see that the treatment system applied in electrocoagulation under optimal conditions obtained a removal efficiency of 94.70% for turbidity, 92.80% for color, and 73.42% for COD. After treatment by electrocoagulation under optimal conditions, the treated effluent was sent to dissolved air flotation, which provided an evolution in the level of treatment. In this context, the effluent now presents 96.84% removal for turbidity, 95.48% for color, and 81.13% for COD. Thus, there was an advance in the effluent treatment, indicating that the DAF proved to be an attractive complementary step, mainly for removing organic matter.

IV. CONCLUSIONS

The treatment system consisting of two stages, electrocoagulation, and dissolved air flotation, proved efficient when applied to the effluent from slaughterhouses and pork slaughterhouses. Despite the effluent's high organic load, color, and turbidity, the results achieved with the two combined techniques are exciting from the point of view of technical feasibility. It was possible to obtain removals of 96.84% for turbidity, 95.48% for color, and 81.13% for COD, using the optimal operating conditions for each step.

In addition to the high treatment efficiency, the optimized conditions for the electrocoagulation step (current density of 3 mA.cm^{-2} and electrolysis time of 10 minutes) provided energy consumption of 333.76 ± 0.515 Wh.m^{-3}, a value much lower than that found in the literature. This good performance may be related to the geometry of the electrochemical reactor, in which the sacrificial electrodes in the form of concentric tubes can improve the dissipation of the produced aluminum ions, in addition to facilitating the flow of generated microbubbles.

An unfavorable factor of electrocoagulation is the residual concentration of metal ions. In this sense, the residual aluminum concentration ranged from 13.2 to 34.2 mg.L^{-1}, a value compatible with the reports found in the literature, however, which suggests the need for a polishing step in the treatment, seeking metal removal.

In future work, it is possible to seek a new equilibrium condition between the two techniques, using milder conditions in the electrochemical treatment (to reduce the residual aluminum concentration) and enhancing the dissolved air flotation stage.

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