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Technical Article

Efficiency of electrocoagulation in the treatment of laundromat greywater

Tratamento por eletrofloculação de efluentes oriundos de lavandeiras domésticas

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ABSTRACT

The high consumption of water and the generation of greywater in laundromats underscore the need to investigate advanced treatment techniques to reuse this effluent. Based on the estimated growth figures of the laundromat sector in Brazil, this study looked into the efficiency of electrocoagulation to treat laundromat greywater. Electrodes were connected to an EC reactor on a monopolar parallel connection mode, with electric current of 6 A and current density of 400 A.m^2. The highest efficiency to treat laundromat greywater was observed at a distance of 15 mm between electrodes, voltage of 17.14 V, and operation time of 30 min, when the removal values of apparent color, true color, turbidity, biochemical oxygen demand, chemical oxygen demand, and surfactants were 92, 97, 88, 91, 98, and 96%, respectively. Electrode consumption was measured at 1.82 g.h, while energy consumption was 20.54 kWh.m^3 and the total cost was US$ 4.10 per cubic meter of treated effluent. However, despite the high efficiency of the treatment, reuse of treated laundromat effluent requires polishing in order to meet the standards defined by Brazilian regulations.

Keywords: laundromat; electrocoagulation; electrolytic treatment; greywater; effluent.

RESUMO

O elevado consumo de água potável e a consequente geração de efluentes associados ao segmento de lavanderias domésticas justificam o estudo de tratamentos avançados que proporcionem o reuso dessas águas. Considerando-se uma perspectiva de crescimento desse setor em nível nacional, esta pesquisa avaliou a eletrocoagulação como tecnologia de tratamento de tais efluentes. Foram executados testes de bancada utilizando eletrodos em alumínio, arranjados como monopolar paralelo. A corrente elétrica e a densidade de corrente foram fixadas em 6A e 400A.m², respectivamente. Entre as variáveis avaliadas estão a distância entre eletrodos, o tempo de operação, o tipo de roupa, a utilização de alvejante e o suporte para eletrólise. O melhor tratamento foi obtido sem a utilização do suporte para eletrólise, para uma distância entre eletrodos de 15 mm, tensão elétrica aplicada no sistema de 17,14 V e tempo de operação igual a 30 min. Nessas condições, as eficiências do tratamento obtidas foram de 92% para cor aparente, 97% para cor verdadeira, 88% para turbidez, 91% para demanda bioquímica de oxigênio, 98% para demanda química de oxigênio e 96% para surfactantes. O sistema resultou no consumo de eletrodo de 1,83 g.h e no consumo de energia elétrica igual a 20,57 kWh.m³. O custo final do tratamento foi calculado em US$ 4,10. m³ de efluente tratado. Embora tenham sido obtidas elevadas remoções nas concentrações dos poluentes, para o reuso do efluente ainda é necessário um tratamento adicional.

Palavras-chave: lavanderia doméstica; eletrocoagulação; tratamento eletrolítico; águas cinzas; efluentes.

INTRODUCTION

The management and reuse of water are essential elements from both the legal and economic perspectives in environmental sciences, underscoring the importance of clean technologies worldwide (CHAROENLARP *et al.*, 2009). However, besides the scarcity of government incentives, the implementation of clean technologies in Brazil is restrained by the limited or even inexistent legal instruments created for this purpose.

More specifically in the laundromat and industrial laundry sector in Brazil, a trade association recommends the sensible use of water and the reuse of treated effluents (SINDILAV, 2018). The industry body also estimates the number of operating laundry establishments in the country at 8,500, of which 6,500 are laundromats and 2,000 are industrial laundry establishments (SINDILAV, 2018). Together, these laundromats and industrial laundries employ 52,520 people directly with a yearly revenue of US$ 1,910,000,000.00. In addition, the

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2018 market expansion of the sector has been calculated at 5% in the next 5 years (SINDILAV, 2018).

Environmental aspects such as water consumption and volume of effluents bear significant relevance in the laundromat sector. Of a characteristic color, the greywater generated is alkaline, turbid, and includes soaps, detergents, and organic matter. These effluents are quite similar to the industrial wastewater produced by textile factories or the typical industrial operations of the textile sector such as dyeing. In this sense, several technologies have been developed to treat and reuse laundromat greywater. For example, (LI *et al.*, 2009) evaluated the effectiveness of technologies used to treat municipal wastewater and concluded that electrolytic treatment is a technically and economically feasible option.

For (CRESPILHO *et al.*,2004), electrocoagulation (EC) comprises four stages:

a) the electrochemical generation of the coagulant;
b) adsorption, neutralization, and sweeping;
c) electroflocculation; and
d) the flotation of contaminants in the effluent.

According to the study by (AOUDJ *et al.*, 2010), iron and aluminum electrodes are the most often used. The reactions that take place on the aluminum electrode are as follows Equation 1, 2, 3:

Anode: $Al \longrightarrow Al^{3+} + 3e^{-}$ (1)

Cathode: $Al^{3+} + 6H_2O \longrightarrow Al(H_2O)_6^{3+}$ (2)

Formation of coagulant: $Al(H_2O)_6^{3+} \longrightarrow Al(OH)_3(s) + 3H^{+}$ (3)

During the electroflocculation stage, the surface area of recently electrogenerated flocs is significant, which induces the fast adsorption of soluble organic compounds and colloidal particles. At the end of the process, these flocs are easily removed from the aqueous medium by sedimentation or flotation (AOUDJ *et al.*, 2010).

The literature has underscored the overall effectiveness of EC to treat water and effluents. For example, (SADEDDIN *et al.*, 2011) and (HASHIM *et al.*, 2017) obtained positive results in the treatment of water for drinking purposes. Also, EC has been investigated in the treatment of greywater (JUNG *et al.*, 2015) and was proved effective to treat wastewater from tanneries (MÓDENES *et al.*, 2012). (BARZEGAR *et al.*, 2019) obtained positive results in the treatment of greywater using EC/ozonation. The results showed that with 60 min electrolysis time, at pH = 7.0, 47.4 mg/L ozone and 15 mA/cm² current density, 70% of total organic carbon (TOC) and 85% of chemical oxygen demand (COD) were removed. (BARISÇI *et al.*, 2016) studied the EC to treat domestic greywater. The highest COD removal was obtained with the Al–Fe–Fe–Al hybrid combination and the highest efficiency was obtained with current density of 1 mA/cm².

(NI'AM *et al.*, 2007), (CHOU *et al.*, 2009), (SOLAK *et al.*, 2009), and (MERZOUK *et al.*, 2009a) investigated the use of EC in the treatment of various kinds of industrial effluents. The recent research obtained removal efficiencies for various items of the textile wastewater. Considering current density 11.55 mA/cm², interelectrode distance 1 cm, and retention time 10 min, the removal values were 83, 68, 81.6, 86.5, and > 92.5% for biochemical oxygen demand (BOD), COD, turbidity, surfactants, and color, respectively. In addition, EC is used in the treatment of wastewater from carwashes (KARA, 2013; EL-ASHTOUKHY *et al.*, 2015; MOHAMMADI *et al.*, 2017). (KARA, 2013) using Al electrodes obtained 76.3, 99.1, and 99.8% removals for COD, color, and turbidity, respectively.

However, the applicability of EC in the treatment of effluents of the textile industry and dyeing operations has also been evaluated. (KOBYA *et al.*, 2009), (CHAROENLARP *et al.*, 2009), (MERZOUK *et al.*, 2009b), (ZHANG *et al.*, 2009), (AOUDJ *et al.*, 2010), (PHALAKORNKULE *et al.*, 2010), (EL-ASHTOUKHY *et al.*, 2010, 2015), (BANI-MELHEM *et al.*, 2012), (YUKSEL *et al.*, 2012), and (AKYOL, 2012) found that the efficiency of EC to remove color, turbidity, and organic matter from these effluents may reach 90%.

Recently, (BILIŃSKA *et al.*,2020) obtained 84% of color removal in a short duration of 8 min using EC for the treatment of a highly polluted industrial wastewater originated in the dyeing of cotton. In contrast, (TAVANGAR *et al.*, 2019) investigated the utility of EC (Al electrode) in the treatment of a real textile wastewater and achieved about 64% of COD removal and 94% of color removal.

(GILPAVAS *et al.*, 2020) studied the sequential electrocoagulation + electrooxidation + activated carbon adsorption (EC + EO + AC) process for the treatment of an industrial textile wastewater. The results of EC treatment showed the removal of 94, 45, and 40% for the dye, COD, and TOC, respectively. The system operated with current density of 5 mA/cm², pH 9.3, 60 rpm, and 10 min of electrolysis time.

In another work, (GILPAVAS *et al.*, 2019) evaluated the potential application of sequential electrocoagulation + Fenton (EC + F) or photo-Fenton (PF) + activated carbon adsorption (PF + AC) for the treatment of textile wastewater. The optimal performance of EC was achieved with Fe electrodes operating during 10 min of electrolysis time, 10 mA/cm² current density, 60 rpm, and pH 7. At these conditions, EC allowed the removal of 94% of the dye's color, 56% of the COD, and 54% of the TOC.

Finally, the combination of EC and O_3 to treat a real industrial wastewater containing Reactive Black 5 (RB5) was studied by (BILIŃSKA *et al.*, 2019). More than 95% color removal was achieved in less than 18 min.

The efficiency of EC is a function of a variety of parameters, such as initial pH, electric conductivity, initial effluent concentration, treatment time, type of electrode, distance between electrodes, current density, and voltage (KOBYA *et al.*, 2009; CHAROENLARP *et al.*, 2009; AOUDJ *et al.*, 2010; JANPOOR *et al.*, 2011; BANI-MELHEM *et al.*, 2012; AKYOL, 2012). Research has shown that the addition of salts may affect the efficiency of treatment with EC (CHOU *et al.*, 2009; AOUDJ *et al.*, 2010). The use of NaCl as supporting electrolyte in EC has been discussed in the literature (AOUDJ *et al.*, 2010). Nascimento et al. (2017), when addressing the treatment by electrochemical processes, reported several studies that mention the advantages of the presence of chloride ions in the effluent. In addition to assisting in the optimization of the electroflotation process, there occurs a formation of the hypochlorite ion, which helps in the disinfection of the effluent.

In view of the organizations need to tackle in order to adapt operations based on best environmental practices, the enforcement of stricter environmental regulations (compliance with BRASIL, 2011), the potential growth of the laundromat sector in Brazil, and the possibility to reduce operation costs reusing water, this study assessed the applicability of EC in the treatment of effluents from laundromats.

METHOD

Origin and characteristics of the effluent

The main objective of this study was to conceive an effluent that could replicate the greywater produced by laundromats, considering variables of the washing process such as the type of clothes washed and use of bleach. In the effort to effectively control these variables, we decided to use two kinds of effluent, namely, E_1 (which included color-safe bleach) and E_2 (without bleach). Both were obtained as a 25-L sample of the first operation stage of a washing machine using a program suitable to wash dark clothes and 118 g of commercial washing powder.

Briefly, E_1 was obtained as six replicates: E_{1-1}, E_{1-2}, E_{1-3}, and E_{1-6} were collected washing white clothes such as underwear, pajamas, light T-shirts, wool jumpers, bedding, and towels, while E_{1-4} and E_{1-5} were obtained washing colored clothes like denim trousers, blouses, and dark T-shirts. And, E_2 was used as seven replicates: E_{2-1}, E_{2-2}, E_{2-4}, E_{2-6}, and E_{2-7} were obtained washing light clothes, and E_{2-3} and E_{2-5} were obtained washing colored clothes. The physicochemical characteristics of the raw effluents used in assays are presented in "Results and Discussion" section.

Experimental apparatus

The EC bench reactor system was formed by a 5 L glass tank with a tap, which was used to collect the treated effluent. Aluminum 6351 electrodes were connected to the reactor on a monopolar parallel connection mode taking special care so that they were immersed in the laundromat greywater. The aluminum content of electrodes varied between 97.8% and 98.6%. Electrodes also contained silicon (0.3 – 0.6%), iron (0.1 – 0.3%), copper (0.1%), manganese (0.1%), magnesium (0.4 – 0.6%), chromium (0.05%), zinc (0.2%), titanium (0.1%), and other elements (0.05%).

Electrodes measured 50 mm (W) × 150 mm (L) × 3 mm (T), accounting for an area of 75 cm^2 and electrode surface/volume ratio of 15 cm^2/L. Initial mass of electrodes was approximately 90 g.

The EC bench reactor system was conceived based on the studies by (KOBYA *et al.*, 2009), (CHAROENLARP *et al.*, 2009), (AOUDJ *et al.*, 2010), (JANPOOR *et al.*, 2011), (BANI-MELHEM *et al.*, 2012), and (AKYOL, 2012) (Figure 1).

Experimental procedures to determine efficiency of electrocoagulation

EC runs were conducted in a batch benchtop reactor at room temperature. Continuous electric current was set at 6 A. Current density (δ) was calculated substituting the current used (6 A) and the area of both electrodes (0.015 m^2) in Equation 4.

$$\delta = \frac{i}{A_{anode}} \rightarrow \delta = \frac{6\ A}{0.015\ m^2} \rightarrow \delta = 400\ A/m^2 \quad (4)$$

According to the study by (KOBYA *et al.*, 2009), δ should be >150 A/m^2.

The voltage (U) needed to operate the system at a distance between electrodes of 5, 15, and 20 mm was defined using Equation 5. The mean electrical conductivity (k) is 3.5 µS/cm (Table 1), or 0.35 mS/m.

$$U = \frac{\delta \times d}{k} \qquad U = \frac{400 \times 0.005}{0.35}\ \ U = 5.71\ V \qquad U = \frac{400 \times 0.015}{0.35}\ \ U = 17.14\ V \qquad U = \frac{400 \times 0.020}{0.35}\ \ U = 22.86\ V \quad (5)$$

Apparent color, true color, turbidity, pH, electrical conductivity, BOD, COD, surfactants, chlorides, and residual chloride of the laundromat effluents treated by EC were determined using the methodologies described in standard methods (APHA, 2012). Total and thermotolerant coliforms were established using the Colilert method (IDEXX LABORATORIES, 2018). The qualitative evaluation of the sludge obtained was conducted in an X-ray fluorescence (XRF)

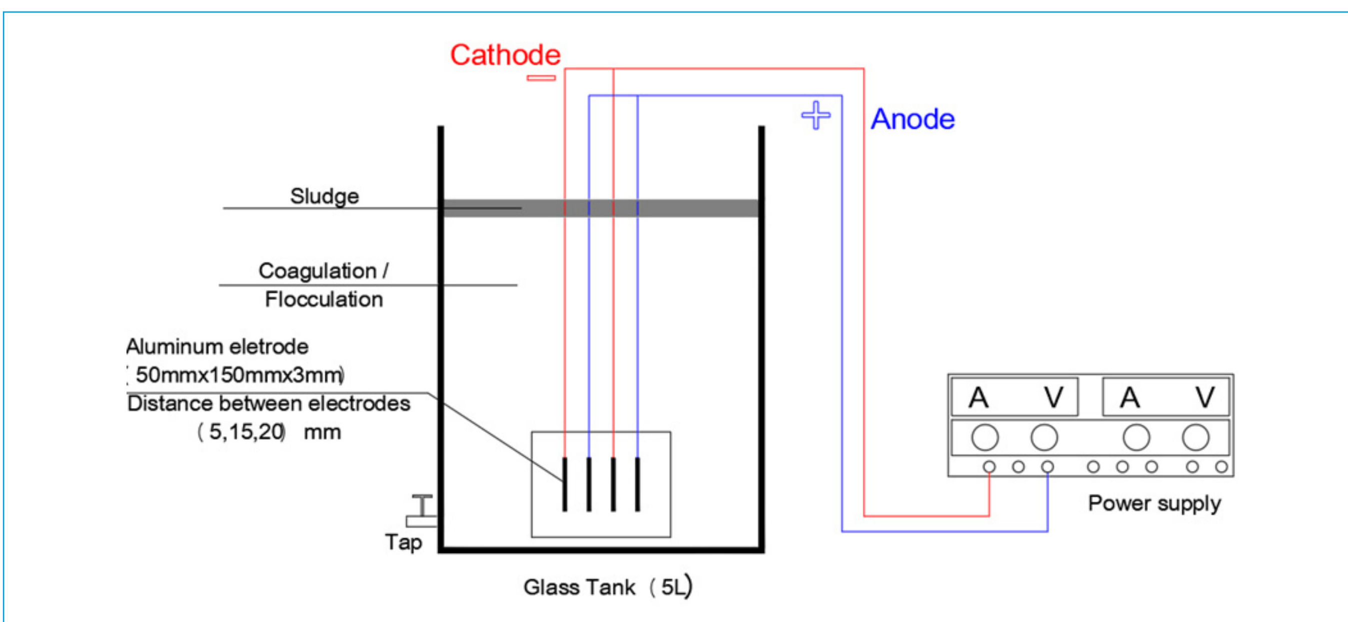

Figure 1 – Electrocoagulation bench reactor used to treat two kinds of laundromat effluents using electrocoagulation.

Table 1 – Characteristics of the assays carried out to test the efficacy of electrocoagulation to treat two kinds of laundromat effluents.

Test	Distance between electrodes (mm)	Addition of NaCl (g.L)	Time (min)	Sample	Parameters analyzed
$E_{1\text{-}1}$ $E_{1\text{-}2}$ $E_{1\text{-}3}$	5 (d_5)	No NaCl (S_0)	60 (T_{60})	Raw, 60 min	Apparent color, true color, turbidity, pH, BOD, COD, surfactants, residual chlorine
				15, 30, 45 min	Apparent color, true color, turbidity, pH
$E_{1\text{-}4}$ $E_{1\text{-}5}$	5 (d_5)	No NaCl (S_0)	180 (T_{180})	Raw, 180 min	Apparent color, true color, turbidity, pH, BOD, COD, surfactants
				15, 30, 45, 60 min	Apparent color, true color, turbidity, pH
$E_{1\text{-}6}$	5 (d_5)	No NaCl (S_0)	180 (T_{180})	Raw, 180 min	Apparent color, true color, turbidity, BOD, COD, surfactants, total and thermotolerant coliforms
				15, 30, 45, 60 min	Apparent color, true color, turbidity, pH
$E_{2\text{-}1}$	20 (d_{20})	No NaCl (S_0); addition of 0.25 g.L (S_{25})	60 (T_{60})	Raw, 60 min	Apparent color, true color, turbidity, pH, conductivity, chlorides, BOD, COD, surfactants
				15, 30, 45 min	Apparent color, true color, turbidity, pH, conductivity
$E_{2\text{-}2}$ $E_{2\text{-}3}$ $E_{2\text{-}4}$	20 (d_{20})	No NaCl (S_0); addition of 0.25 g.L (S_{25}) and 0.50 g.L (S_{50})	60 (T_{60})	Raw, 60 min	Apparent color, true color, turbidity, pH, conductivity, chlorides, BOD, COD, surfactants
				15, 30, 45 min	Apparent color, true color, turbidity, pH, conductivity
$E_{2\text{-}5}$ $E_{2\text{-}6}$	15 (d_{15})	No NaCl (S_0); addition of 0.25 g.L (S_{25}) and 0.50 g.L (S_{50})	60 (T_{60})	Raw, 60 min	Apparent color, true color, turbidity, pH, conductivity, chlorides, BOD, COD, surfactants
				15, 30, 45 min	Apparent color, true color, turbidity, pH, conductivity
$E_{2\text{-}7}$	5 (d_5)	No NaCl (S_0)	60 (T_{60})	Raw, 60 min	Apparent color, true color, turbidity, pH, conductivity.
				15, 30, 45 min	Apparent color, true color, turbidity, pH, conductivity

BOD: biochemical oxygen demand; COD: chemical oxygen demand.

spectrometer. The characteristics of EC runs and the parameters of the treated effluents evaluated are shown in Table 1.

In addition to the parameters analyzed and listed in Table 1, we determined electrode consumption, evaluated electrical energy demand, calculated the cost of EC, and carried out a qualitative analysis of the sludge obtained. In total, 12 tests were carried out to evaluate the efficiency of EC. In brief, electrode consumption was calculated using Equations 6 and 7 (Faraday's law), while the consumption of electrical energy was estimated using Equation 8.

$$\phi = \frac{\Delta M_{exp}}{\Delta M_{calc}} \times 100 \quad (6)$$

$$\Delta M_{theor} = C_{electrode} = \frac{i \times t \times M}{z \times F} \quad (7)$$

$$P = C_{energy} = \frac{U \times i \times t}{V \times 1{,}000} \quad (8)$$

where:

i= applied electrical current (A);

t = time current was applied (s);

M = molar mass of the predominant element in the electrode (g.mol);

M_{exp} = mass of electrode consumed during the experiment (g); z = number of electrons involved in the oxidation reaction (for aluminum, z = 3);

F = Faraday constant (9.65×10^4 C/mol);

∅ = efficacy of current (%);

M_{calc} = $C_{electrode}$ = calculated mass consumption of electrode (g);

P = C_{energy} = Energy consumption (kWh/m³);

U = voltage (V);

t = time current was applied (h); and

V = volume of treated effluent (m³).

Operation costs were calculated using Equation 9 (KOBYA *et al.*, 2009).

$$\text{Operational cost} = aC_{energy} + bC_{electrode} \quad (8)$$

where:

$C_{electrode}$ = mass of electrode consumed during the experiment (g/h·m³);

C_{energy} = energy consumption (kWh/m³);

a = cost of kWh in the municipality of São Leopoldo, state of Rio Grande do Sul, Brazil; and

b = cost of aluminum in the municipality of São Leopoldo, state of Rio Grande do Sul, Brazil.

Statistical analyses

The results obtained were tested using the software SPSS version 22 for Windows. The analysis of variance (ANOVA) was carried out using the ANOVA software and the Tukey test. All hypotheses were tested at a 5% probability level ($p < 0.05$).

RESULTS AND DISCUSSION

Characterization of the raw effluent

Table 2 shows the physicochemical characteristics of the raw effluents used in assays.

The characterization of the raw effluent presented in Table 2 was carried out based on an analysis of the influence of the kind of clothes: white ($E_{1\text{-}1}$, $E_{1\text{-}2}$, $E_{1\text{-}3}$, $E_{1\text{-}6}$, $E_{2\text{-}1}$, $E_{2\text{-}2}$, $E_{2\text{-}4}$, $E_{2\text{-}6}$, and $E_{2\text{-}7}$) or colored ($E_{1\text{-}4}$, $E_{1\text{-}5}$, $E_{2\text{-}3}$, and $E_{2\text{-}5}$). No statistically significant differences were observed in true color ($p = 0.198$), turbidity

Table 2 – Characteristics of two raw laundromat effluents used to analyze the efficacy of electrocoagulation.

Tests	Apparent color (mg Pt Co.L)	True color (mg Pt Co.L)	Turbidity (NTU)	Electrical conductivity (µS. cm)	pH	Chlorides (mg.L)	BOD (mg.L)	COD (mg.L)	Surfactants (mg.L MBAS)	Residual chlorine (mg.L)	Total coliforms (MPN.100 mL)
E_{1-1}	5840.0	5150.0	512.0	-	10.2	-	710.0	3238.0	191.4	<1.0	-
E_{1-2}	5650.0	3530.0	830.0	-	10.2	-	630.0	2580.6	164.2	<1.0	-
E_{1-3}	3070.0	2310.0	590.0	-	10.2	-	590.0	2631.2	144.9	<1.0	-
E_{1-4}	-			-	9.9	-		3845.5	223.9	-	-
E_{1-5}	4100.0	3180.0	363.0	-	10.3	-	360.0	2934.8	165.3	-	-
E_{1-6}	-			-	10.2	-	270.0	2833.6	169.5	-	<1.0
Mean	*4665.0*	*3542.5*	*573.8*	-	*10.1*	-	*512.0*	*3010.6*	*176.5*	-	-
Standard deviation	*1141.7*	*1028.9*	*168.9*	-	*0.1*	-	*167.9*	*431.0*	*25.1*	-	-
Coefficient of variation (%)	*24*	*29*	*29*	-	*1*	-	*33*	*14*	*14*	-	-
E_{2-1}	1220.1	1220.1	335.0	4.2	11.3	-	-	658.2	-	-	-
E_{2-2}	528.9	369.0	117.0	2.9	10.1	5.0	50.0	402.7	2.0	-	-
E_{2-3}	143.4	649.4	156.0	4.5	9.9	5.5	160.5	589.7	2.6	-	-
E_{2-4}	907.0	724.5	237.0	3.6	11.1	6.5	94.0	607.7	1.7	-	-
E_{2-5}	820.2	593.2	229.0	3.5	8.7	6.1	148.5	528.6	1.3	-	-
E_{2-6}	1151.8	700.4	325.0	2.6	10.8	4.3	132.5	684.8	1.8	-	-
E_{2-7}	1406.0	1100.0	103.0	3.1	10.2	-	-	-	-	-	-
Mean	882.5	765.2	214.6	3.5	10.3	5.5	117.1	578.6	1.9	-	-
Standard deviation	402.9	273.8	86.9	0.6	0.8	0.8	40.4	93.1	0.4	-	-
Coefficient of variation (%)	46	36	40	18	8	14	34	16	23	-	-

NTU: Unidade Turbidimétrica Nefelométrica; BOD: biochemical oxygen demand; COD: chemical oxygen demand. Subscript numbers indicate the effluent and respective replicates (E_{1-1}: effluent 1, replicate 1). Itálico: média de cada uma das colunas.

(p = 0.773), conductivity (p = 0.231), chlorides (p = 0.597), BOD (p = 0.517), and surfactants (p = 0.071) (ANOVA, $p < 0.05$). Only apparent color (p = 0.049) and COD (p = 0.031) differed statistically between raw effluents. The results indicate that the kind of clothes washed does not significantly affect the physicochemical characteristics of laundromat effluents.

In turn, the evaluation of the effect of color-safe bleach in the composition of effluents showed that, except for pH (p = 0.715), the parameters of E_1 and E_2 differed significantly (p = 0.000 for true color, apparent color, turbidity, COD, BOD, and surfactants). In other words, color-safe bleach affected the characteristics of laundromat effluents due to the presence of hydrogen peroxide in the formulation of the product used, increasing the levels of contaminants due to the oxidation reactions induced.

Due to the statistically significant differences between E_1 and E_2, the results are shown separately.

E_1 analysis

Table 3 shows the results of the analysis of E_1.

Considering treatment times, the results show that most parameters of E_1 varied significantly after treatment with EC (apparent color; p = 0.005; true color: 0.013; turbidity: p = 0.002; p p = 0.009; COD: p = 0.000; surfactants: p = 0.000). The only parameter that did not vary statistically was BOD (p = 0.055). These results indicate that treatment time affects the efficacy of EC.

Figure 2 illustrates this result clearly. The analysis revealed no statistically significant differences for E_1 treated for T_{60} and the shorter treatment times. The efficiency obtained at T_{180}, compared with T_{60} (Table 3), shows that minimum EC treatment time for laundromat effluent with color-safe bleach should be 180 min. The Tukey test confirms this result. Statistically significant differences were observed between the values obtained at T_{180} by comparison with T_0, T_{15}, T3$_0$, and T_{45}.

Research has shown that operation time influences the efficacy of EC. (JANPOOR *et al*. 2011) used EC to treat laundromat greywater for 15, 30, 45, 60, 75, and 90 min. The best results were obtained treating the effluent for 60 min, when COD, color, and turbidity values were improved by 89.3, 88.0, and 94.4%, respectively, which contrasts with the findings obtained in this study. The authors maintained that operation times over 60 min did not improve these parameters significantly. However, the best results were obtained at a distance of 15 mm between electrodes and voltage of 30 V, which are different from the values used in this study.

Another factor that may explain these differences is the condition of the raw effluent. Since E_1 contained more impurities due to the use of color-safe bleach, the efficacy of treatment was reached using longer treatment time. This was also observed for E_2.

E_2 analysis

The results obtained for the treatment of E_2 using EC are shown in Tables 4 – 6.

Table 3 – Efficacy of electrocoagulation to treat laundromat effluent E_1 (with color-safe bleach) when distance between electrodes was 5 mm (d_5) and no NaCl was used as supporting electrolyte.

Parameter	Raw effluent: T_0	Treatment times (min)					Efficiency (%)	
		T_{15}	T_{30}	T_{45}	T_{60}	T_{180}	T_{60}	T_{180}
Apparent color (mg Pt Co.L)	4665.0 ± 1318.3	4557.5 ± 1323.3	3555.0 ± 1417.9	3562.5 ± 1253.8	3247.5 ± 1067.3	533.7 ± 288.0	30	89
True color (mg Pt Co.L)	3452.5 ± 1188.1	3030.0 ± 580.7	2542.5 ± 1205,8	2745.0 ± 1058.6	2400.0 ± 943.1	390.3 ± 343.5	32	89
Turbidity (NTU)	573.8 ± 195.1	478.8 ± 160.7	386.3 ± 111.5	305.8 ± 124.7	273.6 ± 127.4	64.0 ± 36.8	52	89
pH	10.1 ± 0.1	10.4 ± 0.1	10.4 ± 0.1	10.5 ± 0.2	10.5 ± 0.2	10.2 ± 0.2	-	-
BOD (mg.L)	512.0 ± 187.7	-	-	-	346.7 ± 47.3	155.0 ± 49.5	32	70
COD (mg.L)	3010.6 ± 472.2	-	-	-	1830.0 ± 129.8	573.3 ± 255.8	39	81
Surfactants (mg.L MBAS)	176.5 ± 27.5	-	-	-	112.9 ± 14.3	10.3 ± 0.5	36	94
Total coliforms (MPN.100 mL)	<1.0	-	-	-	-	< 1.0	-	-
Total coliforms (MPN.100 mL)	<1.0	-	-	-	-	< 1.0	-	-
Residual chlorine (mg.L)	<1.0	-	-	-	< 1.0	-	-	-

BOD: biochemical oxygen demand; COD: chemical oxygen demand.

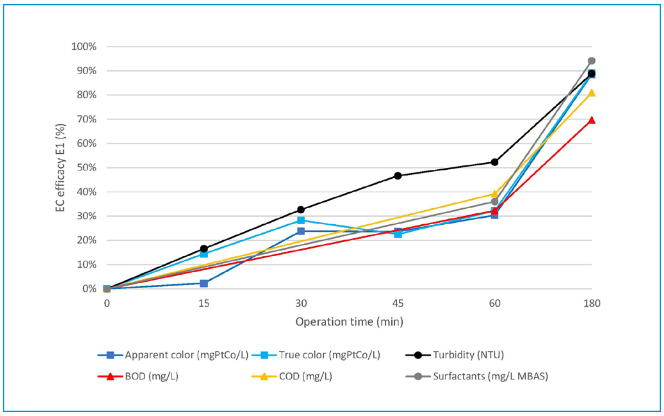

Figure 2 – Efficacy of electrocoagulation to treat laundromat greywater.

Table 4 – Efficacy of electrocoagulation to treat E_2 (greywater with no color-safe bleach) at a distance of 5 mm between electrodes with no supporting electrode.

Parameter	Treatment time (min): d_5					Efficiency (%) T_{60}
	T_0	T_{15}	T_{30}	T_{45}	T_{60}	
Apparent color (mg Pt Co.L)	1406.0	721.0	203.0	196.0	267.0	81
True color (mg Pt Co.L)	1100.0	203.0	69.0	71.0	72.0	93
Turbidity (NTU)	103.0	80.0	6.1	13.2	23.0	78
Conductivity (μS.cm)	3.1	3.2	2.8	2.9	3.2	-
pH	10.2	9.7	9.7	9.9	10.0	-

Effect of distance between electrodes (d)

The results obtained show that apparent color ($p = 0.000$), turbidity ($p = 0.001$), and pH ($p = 0.000$) differed significantly using distinct distances between electrodes (ANOVA, $p < 0.05$). Also, the Tukey test indicated that apparent color ($p = 0.000$) and turbidity ($p = 0.002$) varied significantly (ANOVA, $p < 0.05$) between d_5 and d_{15} and between d_5 and d_{20}. Also, pH differed significantly when d_5 and d_{20} ($p = 0.010$) and d_{15} and d_{20} ($p = 0.000$) were used.

From the statistical analysis and the efficacy values obtained (Tables 4–6), we can conclude that d_{15} is the optimum distance between electrodes to treat the laundromat effluents in this study. This agrees with the findings by (JANPOOR *et al.* 2011) and (AOUDJ *et al.*, 2010), who used aluminum electrodes and reported that the best results were obtained using electrodes separated by 15 mm. (AOUDJ *et al.*, 2010) concluded that the efficacy of EC diminishes when the distance between electrodes is larger than 15 mm. This was also observed in this study, when efficacy of EC using d_{20} was lower than the value obtained with d_{15}.

Effect of treatment time (T)

For d_{15}, the values of true color ($p = 0.010$), apparent color ($p = 0.000$), turbidity ($p = 0.010$), BOD ($p = 0.005$), and COD ($p = 0.017$) differed significantly across the treatment times stipulated (ANOVA). The Tukey test showed that the values of true color and turbidity varied significantly between T_0 and T_{30}, T_{45}, and T_{60}. In turn, apparent color varied significantly between T_0 and T_{15}, T_{30}, T_{45}, and T_{60}. No statistically significant differences were observed in the parameter between T_{15}, T_{30}, T_{45}, and T_{60}.

Therefore, the statistical analyses and the efficiency values shown in Tables 4–6 indicate that a 30-min EC run is enough to clean laundromat greywater when the distance between electrodes is 15 mm.

Using the same operation parameters evaluated in this study, (JANPOOR *et al.* 2011) and (AOUDJ *et al.*, 2010) obtained the highest efficiency to reduce COD, color, and turbidity using a 60-min EC run. In contrast, (AKYOL, 2012) and (KOBYA *et al.*, 2009), reached optimal results with 15 and 10 min, respectively. Nevertheless, the distances between aluminum electrodes were 10 and 11 mm.

Table 5 – Efficacy of electrocoagulation to treat E_2 (greywater with no color-safe bleach) at a distance of 15 mm between electrodes with no supporting electrode.

Parameter	Treatment time (min): d_{15}					Efficiency (%) T_{60}
	T_0	T_{15}	T_{30}	T_{45}	T_{60}	
Apparent color (mg Pt Co.L)	986.0 ± 234.5	490.4 ± 281.4	58.8 ± 26.6	131.4 ± 66.9	75.7 ± 6.9	92
True color (mg Pt Co.L)	646.8 ± 75.8	108.0 ± 77.7	26.6 ± 8.8	27.2 ± 19.2	18.6 ± 0.0	97
Turbidity (NTU)	277.0 ± 67.9	105.5 ± 71.4	7.6 ± 0.0	47.3 ± 29.2	32.7 ± 3.5	88
Conductivity (µS.cm)	3.0 ± 0.6	2.9 ± 0.5	2.8 ± 0.3	3.0 ± 0.5	3.0 ± 0.5	-
pH	9.7 ± 1.5	9.6 ± 1.8	10.1 ± 1.1	10.4 ± 0.9	10.7 ± 1.1	-
Chlorides (mg.L)	5.2 ± 1.2	-	5.1 ± 1.1	-	5.0 ± 1.1	3
BOD (mg.L)	140.5 ± 11.3	-	-	-	12.0 ± 0.0	91
COD (mg.L)	606.7 ± 110.5	-	-	-	10.0 ± 0.0	98
Surfactants (mg.L MBAS)	1.6 ± 0.4	-	-	-	0.1 ± 0.0	96

BOD: biochemical oxygen demand; COD: chemical oxygen demand.

Table 6 – Efficacy of electrocoagulation to treat E_2 (greywater with no color-safe bleach) at a distance of 20 mm between electrodes with no supporting electrode.

Parameter	Treatment time (min): d_{20}					Efficiency (%) T_{60}
	T_0	T_{15}	T_{30}	T_{45}	T_{60}	
Apparent color (mg Pt Co/L)	699.8 ± 466.3	606.1 ± 368.2	207.9 ± 174.1	86.3 ± 37.0	89.8 ± 38.0	87
True color (mg Pt Co/L)	740.7 ± 354.3	388.5 ± 414.9	141.8 ± 167.2	60.8 ± 43.4	48.0 ± 66.3	94
Turbidity (NTU)	211.3 ± 96.5	145.5 ± 92.8	47.0 ± 42.0	29.3 ± 6.0	27.1 ± 22.0	87
Conductivity (µS/cm)	3.8 ± 0.7	3.3 ± 0.4	3.4 ± 0.5	3.4 ± 0.7	3.6 ± 0.5	-
pH	10.6 ± 0.7	10.5 ± 0.9	10.4 ± 0.8	10.3 ± 0.6	10.6 ± 0.6	-
Chlorides (mg/L)	168.8 ± 326.3	-	5.8 ± 0.6	-	46.9 ± 82.5	72
BOD (mg/L)	101.5 ± 55.6	-	-	-	12.7 ± 17.0	88
COD (mg/L)	533.4 ± 113.5	-	-	-	163.3 ± 43.8	69
Surfactants (mg/L MBAS)	2.1 ± 0.5	-	-	-	0.5 ± 0.7	77

BOD: biochemical oxygen demand; COD: chemical oxygen demand.

The ANOVA results demonstrated the significant influence of distance of 20 mm between electrodes on true color ($p = 0.014$), apparent color ($p = 0.008$), turbidity ($p = 0.0030$), COD ($p = 0.002$), and surfactant ($p = 0.027$). The Tukey test demonstrated the significant difference between the values of apparent color and turbidity between T_0 and T_{30} and between T_{45} and T_{60}. True color varied significantly between T_0 and T_{45} and T_{60}. Similarly to the value observed with d_{15}, no statistically significant differences were observed between the values obtained between T_{15}, T_{45}, T_{30}, and T_{60}. Therefore, it is possible to establish T_{45} as the best treatment time when d_{20} is used.

Interference of supporting salt

Figures 3 and 4 show the efficiency of EC to treat laundromat greywater either using or not using a supporting salt.

It is possible to observe that the results of treatment with EC either using or not using NaCl as a supporting salt are similar. The ANOVA and Tukey tests show that removal of apparent color using d_{15} varied significantly for T_{15} ($p = 0.009$), T_{30} ($p = 0.043$), and T_{45} ($p = 0.042$). For T_{60}, significant differences were observed for true color ($p = 0.046$), apparent color ($p = 0.011$), BOD ($p = 0.001$), and COD ($p = 0.001$). When d_{20} was used, the only parameter that varied was the level of chlorides measured at T_{30} ($p = 0.011$) and T_{60} ($p = 0.003$).

Using 2 g/L NaCl, (AOUDJ *et al.*, 2010) obtained efficiency of 98% to remove color of textile wastewater containing dye. The experiment included aluminum electrodes separated by 15 mm and current density of 18.75 A/m^2. The operation time was 60 min and initial pH of the effluent was 6.0.

However, the results obtained in this study show that the use of NaCl as a supporting electrolyte did not significantly improve the efficiency of EC to treat laundromat greywater. The intention to use this supporting electrolyte was to increase the electrical conductivity of the effluent to improve the mobilization of electric charges (AOUDJ *et al.*, 2010; CRESPILHO *et al.*, 2004). Nevertheless, the electrical conductivity from raw effluent was sufficient to promote the treatment.

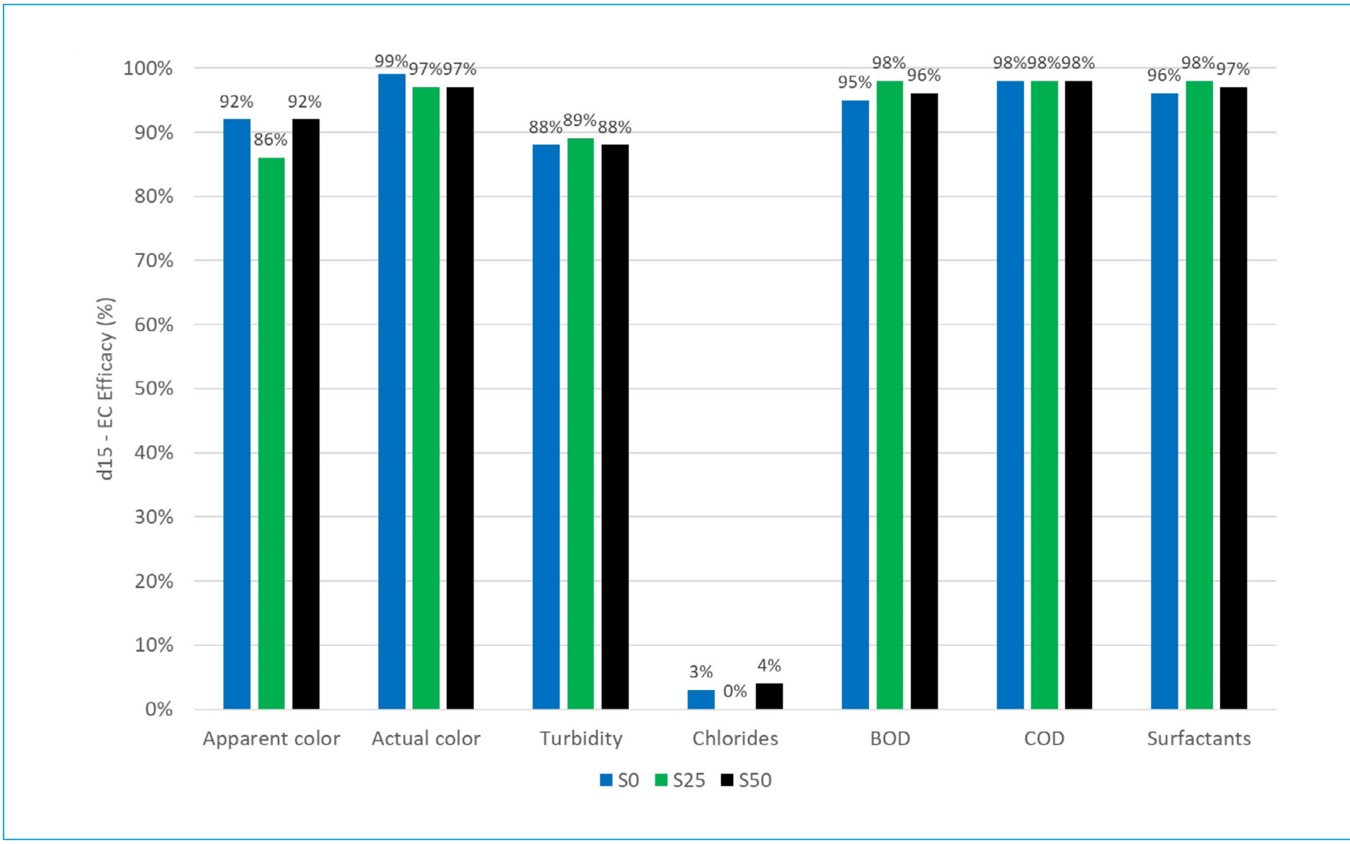

Figure 3 – Efficiency of electrocoagulation to treat two laundromat effluents and use of supporting salt (d_{15}). No NaCl (S_0); addition of 0.25 g.L (S_{25}) and 0.50 g.L (S_{50}). BOD: biochemical oxygen demand; COD: chemical oxygen demand.

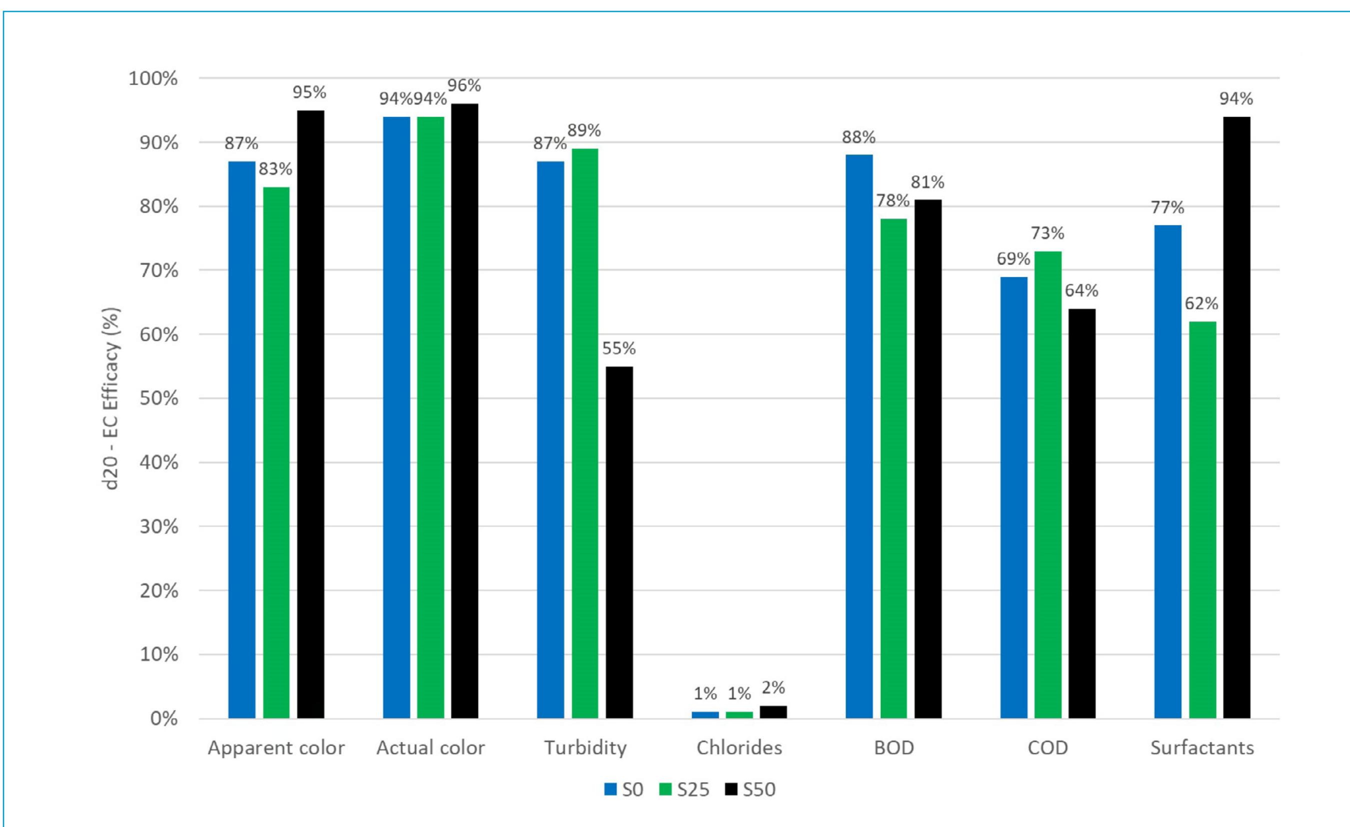

Figure 4 – Efficiency of electrocoagulation to treat two laundromat effluents and use of supporting salt (d_{20}). No NaCl (S_0); addition of 0.25 g.L (S_{25}) and 0.50 g.L (S_{50}). BOD: biochemical oxygen demand; COD: chemical oxygen demand.

Sludge analysis

The analysis of the sludge obtained is shown in Table 7.

As expected, the main element detected in the sludge was aluminum, due to the metallic alloy employed in the manufacture of the electrodes used in this study. Similar results were obtained for sludge in the study by (AKYOL, 2012).

In addition to aluminum, (AKYOL, 2012) detected S, Cr, Fe, Mn as well as SiO_2, TiO_2, CaO, MgO, and P_2O_5. In this study, the trace elements and secondary elements detected were Si, Fe, Cu, Zn, Mg, Mn, and Cr. The presence of these elements in the sludge may also be associated with the electrode alloy.

In turn, the presence of chlorine in the sludge is linked with the tap water used to wash the clothes. The element is used to disinfect water in treatment units. However, the chlorine detected in the sludge may also be associated with the use of NaCl as a supporting electrode.

The presence of the other elements may be ascribed to the dyes in clothes or the composition of the chemicals used in washing.

Operation costs

Table 8 shows the operation parameters calculated using Equations 6 – 8.

Calculated electrode consumption was 2.01 g. Actual electrode consumption varied between 1.83 and 4.47 g/h, which means that the efficiency of the electric current values used varied between 91 and 218%. Efficiency values well over 100% indicate that the current value (6.0 A) used is oversized for a given system.

Therefore, based on the results of this study, the optimal operation parameters of an EC system to treat laundromat greywater are as follows: distance between electrodes = 15 mm; supporting electrolyte (NaCl) = not necessary; current density = 400 A/m^2; voltage = 17.14 V; electric current = 6.0 A; time current is applied = 30 min; volume of treated effluent = 0.005 m^3; initial pH = 10.3; initial electric conductivity = 3.5 μS/cm; efficiency of treatment = removal of apparent color (92%), true color (97%), turbidity (88%), BOD (91%), COD (98%), surfactants (96%); $C_{electrode}$ = 1.83 g/h, or 36.562 g/h m^3; $M_{calculated}$ = 2.01 g; efficiency of current = 91%; and C_{energy} = 20.57 kWh/m^3.

Operation cost was calculated using Equation 9. The cost of kWh (US$ 0.180 after tax, January 2019) and the cost of aluminum (US$ 6.23/kg, January 2019) used were valid for municipality of São Leopoldo, state of Rio Grande do Sul, Brazil. The calculated treatment cost was US$ 4.10/m^3 of treated effluent, of which US$ 2.30/m^3 were due to electrode consumption and US$ 1.80/m^3 were due to electrical energy.

(AKYOL, 2012) estimated the cost to treat paint manufacturing wastewater using aluminum electrodes at €0.129/m^3 (0.16 US/m^3). When iron electrodes were used, the cost was €0.187/m^3 (0.23 US/m^3). (KOBYA *et al.*, 2009), evaluated EC to treat effluents from textiles manufacture and calculated the cost using iron electrodes at €0.50/m^3 (0.61 US/m^3). (BARZEGAR *et al*, 2019) calculated costs for treatment of greywater with EC/ozone and EC/ozone/UV as 1.9 and $ 4.03 m^3 respectively.

Compared with the results obtained by (AKYOL, 2012) and (KOBYA *et al.*, 2009), the operation cost calculated in this study was significantly higher, possibly due to the high values of electric current and voltage used. Another reason may be the price of aluminum, which contributed to increase the final cost of treatment.

Reuse and discharge of effluents

Brazil does not have specific legislation defining effluent reuse standards. Specific legislation stipulates reuse criteria based on the characteristics of the treated effluent (ABNT, 1997). These criteria define the standards of the reuse of wastewater for non-drinking purposes, like washing of floors and toilet flushing, for instance.

The analysis of the quality of the water for reuse in laundromats points to the need to adopt standards that are similar to the ones adopted to characterize tap water, which is described in specific legislation in the country (BRASIL, 2021).

Nevertheless, the results obtained in this study indicate that, despite the removal of color, turbidity, and organic matter of around 90%, the parameters used do not afford to clean laundromat greywater to an extent that meets the criteria defined in Brazilian regulations (ABNT, 1997; BRASIL, 2017). Therefore, this treated effluent requires polishing before reuse.

Table 7 – XRF analysis of sludge obtained treating laundromat greywater by electrocoagulation.

Addition of NaCl	Main elements	Secondary elements	Trace elements
S_0	Al	Cl, Si, S, Fe	Ca, Fe, Mg, Cu, Zn, K, Mn, Cr, Sr, Ga, Br, Si, S, Zr
S_{25}	Al	Cl, Si, S, Fe, Ca	Ca, Fe, Mg, Cu, Zn, K, Mn, Cr, Sr, Ga, Si, S, Zr
S_{50}	Al	Cl, Si, S, Ca, Na	Ca, Fe, Mg, Cu, Zn, K, Mn, Cr, Sr, Ga, Br, Si, S, Zr

Main elements: > 50%; secondary elements: 5% < x < 50%; trace elements: < 5%.

Table 8 – Operation consumption of the EC system used to treat laundromat greywater.

Addition of NaCl (S)	Distance between electrodes (d) mm	Electrode consumption (g.h)	Aluminum consumption (g.h)*	$M_{calculated}$ (g.h)	Efficiency of current (%)
S_0	5	3.31 ± 0.29	3.26 ± 0.29	2.01	162 ± 14
	15	1.86 ± 0.66	1.83 ± 0.65	2.01	91 ± 32
	20	3.67 ± 0.64	3.62 ± 0.63	2.01	180 ± 31
S_{25}	15	3.00 ± 0.87	2.95 ± 0.86	2.01	146 ± 43
	20	3.99 ± 1.09	3.93 ± 1.07	2.01	195 ± 53
S_{50}	15	3.98 ± 0.76	3.92 ± 0.75	2.01	195 ± 37
	20	4.47 ± 1.53	4.40 ± 1.50	2.01	218 ± 75

*Considering the content of aluminum used equal to 98.56%.

Similar conclusions were reached by (CHAROENLARP *et al.*, 2009). To remove turbidity and suspended solids, the authors suggested a filtration process as a means to further treat the effluent after EC. This supplementary process is also valid in this study.

Also, the comparison of the results of this study with the values stipulated in Brazilian regulation (BRASIL, 2011) indicates the need to adjust the pH between 6.0 and 9.0 before discharging treated laundromat effluents in surface waters in the environment.

CONCLUSIONS

The high rates of removal of contaminants (apparent color: 92%, true color: 97%, turbidity: 88%, BOD: 98%, COD: 98%, and surfactants: 96%) confirm the efficiency of EC to treat laundromat greywater. The best operation settings were initial pH of 10.3, mean electrical conductivity of 400 A/m^2, distance between electrodes of 15 mm, voltage of 17.14 V, and operation time of 30 min. Electrode consumption and energy consumption were 1.83 g/h and 20.57 kWh/m^3, respectively. The current efficiency was 91%.

Also, the addition of color-safe bleach affected the quality of the laundromat effluent. Due to the higher levels of contaminants in this effluent, longer treatment times were necessary (T_{180}). Nevertheless, the kind of clothes (whites and colored) did not influence the characteristics of the raw greywater treated.

Electrode consumption accounted for US$ 2.30.m^3 and electrical energy cost US$ 1.80.m^3 to treat laundromat greywater. Together, the treatment operation cost was US$ 4.10.m^3. In this research, a complete economic feasibility study was not performed, only a survey of operating costs. Also, despite the efficacy of EC, the parameters of the treated effluent do not allow reusing it unless a polishing step is adopted, such as a filtration step, for instance, which improves color and turbidity of the treated effluent.

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