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EFFECT OF POTENCIOSTATIC ELECTROCOAGULATION PROCESS PARAMETERS ON THE TREATMENT OF EFFLUENTS FROM CAR WASHING STATIONS: A complete kinetic study

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Abstract

Vehicle wash station effluents (VWSE) are potential contaminants of water resources. These effluents contain metallic compounds such as chromium, lead, zinc, and cadmium, as well as organic contaminants such as surfactants, oils, and greases. As a consequence, these effluents have high chemical oxygen demand (COD) values. In this study, the electrocoagulation (EC) process with aluminum electrodes was used to treat VWSE, with the aim of reducing turbidity, COD, and surfactant concentrations. The studies evaluated the effect of pH, treatment time, electric potential difference, and electric current density on the reduction of these physical-chemical parameters. The experiments were designed using the 22-type full factorial experimental design methodology, with triplicate at the central point. VWSE samples were collected at a single location and on different days. The VWSE without EC treatment presented values of 609 mgo_2 L^{-1} for COD, 66.3 mg L^{-1} for surfactant concentration (MBAS) and 653±208 NTU for turbidity. The electrical conductivity of all samples was adjusted to 900±100 μS cm^{-1} with the addition of a sodium chloride solution (NaCl – 1 M). The results showed that the potentiostatic mode for the EC process presents the greatest efficiency in reducing the physical-chemical parameters of VWSE. It was found that the pH values and treatment time influence the process of reducing the COD, MBAS and

turbidity parameters. With the experimental condition of pH 5.5, with a treatment time of 315 min and an electrical potential difference of 10 V, it was possible to reduce the COD value by 89.0% and the MBAS value by 99.0%.

Keywords: Electrocoagulation Process, Car Wash Wastewater Treatment, COD Reduction in Car Wash Effluents, Aluminum electrodes

1 INTRODUCTION

Water resources are widely used in industrial, urban and rural processes. Consequently, significant volumes of effluents are generated and need to be adequately treated before being released into water bodies, so as not to cause environmental impacts.

Effluents from vehicle wash stations (VWSE) are also sources of contamination of water resources (Monney, 2020). Vehicle wash establishments consume large volumes of water for several related purposes. According to studies reported by Emamjomeh et al. (2019); Ghaly et al. (2021) and Uçar (2017), the volumes of water used by wash stations can vary depending on the type and conditions of the washing processes.

In this sense, there are studies that indicate that between 60 and 150 L of water are used in vehicle washing processes, and in some cases these values may be higher, between 200 and 400 L (Panizza & Cerisola, 2010a; Lau, 2013; Alves et al., 2014; Tamiazzo et al., 2015; Rodriguez Boluarte et al., 2016; Quayson & Awere, 2017; Ndi, 2018; Monney, 2020). Considering that thousands of vehicles are washed daily, the high volume of effluent generated is important and requires attention and processes with efficient technologies for its treatment, with a view to reducing the environmental impacts of VWSEs and mitigating water waste, especially in regions with limited water resource availability. A variety of toxic and recalcitrant compounds are found in VWSEs, including oils and greases, chemicals and solvent-based solutions, toxic metals, gasoline, kerosene, carbon, asphalt, salts, and a considerable amount of detergents (Hamada & Miyazaki, 2004; Panizza & Cerisola, 2010a; Srinivasan & Viraraghavan, 2010; Dadebo et al., 2022). The disposal of effluents containing residual detergents into water bodies results in the formation of foams, which reduce the concentration of dissolved oxygen in the water and negatively interfere with the oxygenation of the aquatic environment (Aboulhassan et al., 2006; Cooper & Kennedy, 2010; Bhatti, 2011; Yuan et al., 2014; Hashim & Zayadi, 2016; Effendi et al., 2017). This effect inhibits the growth of plants and animals that inhabit these environments, which negatively impacts the aquatic ecosystem (Tiwary, 2001; Alade et al., 2011; Yuan et al., 2014).

Several studies have shown that effluents generated by vehicle maintenance and washing establishments have high chemical oxygen demand (COD) values, ranging from 50.0 mg_{O2} $^{L-1}$ to 2050.0 mg_{O2} L^{-1} (Atiyah & Abdul-Majeed, 2019a; El-Ashtoukhy et al., 2015; Fikri et al., 2019; Mohammadi, 2017; Priya & Jeyanthi, 2019; Silva et al.,

2017; Sarmadi et al., 2020). Numerous values within this range or even higher are reported in recent studies carried out by Sarmadi et al. (2020), Monney et al. (2020) and also by Guerreiro Crizel et al. (2024).

Regarding turbidity, most of the values reported for VWSEs are in a range between 109.0 and 5800 NTU as presented in the studies by Aikins and Bokaye, (2015), Tekere et al. (2016), Monney; Donkor and Buamah, (2020) and Sarmadi et al (2020). Regarding the presence of anionic surfactants, which are active substances in the methylene blue test (MBAS), values between 1.00 and 353.0 mg L^{-1} were reported in VWSE effluents (Tekere et al., 2016; Gönder et al., 2017; Silva et al., 2017; Gönder et al., (2019); Emamjomeh et al., (2019) and Sarmadi et al., 2020). The pH of raw VWSE effluents was generally reported to range between 5.0-9.5 in the studies by Sarmadi et al. (2020) and also by Guerreiro Crizel et al. (2024). Regarding the initial OG content of VWSE effluents, there are also reports of a wide range of values, with concentrations between 1.0-1750 mg L^{-1} recorded in the studies by Sarmadi et al. (2020) and Guerreiro Crizel et al. (2024) indicating values between 120-550 mg L^{-1}.

Regarding the presence of toxic metallic species in VWSEs, a variety of concentration values have been reported. For zinc (Zn), values range between 0.01-22.20 mg L^{-1}, while for copper (Cu) between 0.01-14.00 mg L^{-1} (Aikins & Boakye, 2015; Tekere et al., 2016; Sibanda et al., 2019; Sarmadi et al., 2020). As for chromium (Cr), values found are between 0.10 and 3.00 mg L^{-1} (Tekere et al., 2016; Sarmadi et al., 2020). Regarding lead (Pb), values between 0.02 and 7.00 mg L^{-1} have been reported (Tekere et al., 2016; Sibanda, Silvarajan and Tekere, 2019 and Sarmadi et al., 2020; Ghlay et al., 2021).

Considering the polluting potential of VWSEs and the increasing stringency of environmental legislations and regulations in many countries regarding effluent treatment processes, its packaging, and disposal, the implementation of new methodologies and technologies that contribute to the proper treatment of VWSEs has become a priority, aiming to eliminate or reduce their polluting potential and to ensure their reuse or safe disposal in water resources (Rubio & Zaneti, 2009; Zaneti, 2011; Zaneti et al., 2012; Etchepare et al., 2015; Ganiyu et al., 2018).

Several studies have been proposed and applied for effluent treatment, such as advanced oxidation processes (AOPs), adsorption, chemical coagulation, and biological processes (Sun et al., 2009; Saroj et al., 2015; Moradnia et al., 2016; Jaafari et al., 2019; R. Singh & Bhateria, 2020). However, these technologies have some disadvantages, such as long treatment/hydraulic retention time, high energy and chemical reagent consumption, surface clogging, low treatment efficiency, generation of large volumes of sludge, the need for significant areas for installation/operation, and sensitivity to temperature and pH variations (Gernaey et al., 2004; An et al., 2017). However, the electrocoagulation (EC) process is a technology that has been applied with technical and economic feasibility in the treatment of industrial effluents, as it is capable of making the effluent water suitable for disposal into water resources (Núñez et al., 2019; Sarmadi et al., 2020; Ghaly et al., 2021; Guerreiro Crizel et al., 2024).

In EC processes, the electrolytic oxidation technology of a metal anode is explored, based on the definition of specific values of electric currents or electric

potential differences (epd) in electrochemical reactors. The main objectives of this process are to remove solid contaminants dispersed in the effluent, toxic metals and dissolved pollutants. In these operations, EC processes have been an efficient and sustainable alternative, both on an industrial scale and in small facilities (An et al., 2017; Mousazadeh et al., 2021; Guerreiro Crizel et al., 2024; Phu et al., 2025).

The use of EC processes in effluent treatment offers advantages over other processes, such as high efficiency in reducing contaminants, low sludge generation, lower energy and reagent consumption compared to chemical processes, and flexibility of operation in different temperature and pH conditions (AlJaberi et al., 2022; Guerreiro Crizel et al., 2024). These benefits may contribute to the viability and sustainability of EC processes in the treatment of effluents in vehicle wash establishments.

EC processes have recently been studied for the treatment of VWSEs. However, although this technology is a promising process, few studies have yet been dedicated to understanding the effect of different electrochemical conditions on the values of important physical-chemical parameters for the safe disposal of these effluents, such as the effect on the values of COD, turbidity, and surfactant concentration (Guerreiro Crizel et al. (2024).

Since this is an emerging and effective technology, it is increasingly necessary to increase the level of detail of the effect of the electrochemical parameters of this process on the physical-chemical parameters of VWSE effluents, such as the effect of the distance between electrodes (DE), pH, surface area of the electrodes and electrical conductivity, as well as the effect of the values and conditions of electric current or epd. Correlating the effects with these different electrochemical conditions is essential to obtain mathematical models that contribute to the design of electrochemical reactors on a larger scale, simulating a real batch or continuous process in the treatment of VWSE effluents.

This study evaluated the effect of the difference in electric potential, electric current density and treatment time on the efficiency of the EC process with aluminum electrodes in reducing the values of the physical-chemical parameters COD, anionic surfactant concentration, which will be represented by the term methylene blue active substances (MBAS) and turbidity of VWSE effluents. The experiments were organized using the experimental planning methodology and it was possible to obtain a statistical model of correlation between the effects and the process variables, which allowed determining the optimal process conditions for the maximum reduction of the physical-chemical parameters of the VWSE effluent.

2 Materials and methods

2.1 Collection of VWSE Samples

The VWSE effluent was collected from oil-water separator (OWS) tanks at different washing stations located in the city of Chapecó (SC/Brazil). The collection and storage conditions were in accordance with NBR 9898/87 (ABNT, 1987), using 5.0 L polyethylene gallons to collect directly from the OWS tanks and to store the effluent. Next, 4.0 M H_2SO_4 reagent was added to the effluent until reaching pH 2.0 to preserve

the sample in acidic pH conditions and placed under refrigeration (~5 ºC). In the experiments, the acidified effluent samples were used at room temperature (~25 ºC) and the pH was adjusted with 1.0 M NaOH to the range of interest for the experiment.

2.2 Physical-chemical characterization of VWSE

For the physical-chemical characterization of the effluent, the pH, temperature, electrical conductivity, MBAS, turbidity and COD values were measured. The analyses were performed according to the methods standardized by the Standard Methods 22nd edition (APHA, 2012).

The pH of the effluent was measured before and after its treatment with the EC process, using a digital pH meter (Hanna Instruments, model pH 21). The temperature of the VWSE was measured with a mercury thermometer. The electrical conductivity of the VWSE was measured using a benchtop conductivity meter (Quimis, model Q795M).

The MBAS concentration was determined following the 5540C methodology of the Standard Methods (APHA, 2012), however in micronized volumes. For this purpose, 10.0 mL microtubes containing 750 µL of methylene blue (0.3 M), 200 µL of monobasic sodium dihydrogen phosphate washing solution (0.362 M), 3.0 mL of chloroform and 3.0 mL of sample (concentrated or diluted) were used. The determination of MBAS was performed using a colorimeter calibrated in the range of 0.05 to 2.00 mg L^{-1} at a wavelength of 650 nm.

The effluent turbidity analyses were performed using a Spectroquant colorimeter (Merck KGA, Move 100), in the concentration range of 1.0 to 100.0 NTU. For the measurement, 1.0 mL of raw or treated VWSE sample was placed in 10 mL microtubes.

The COD analyses of VWSE were performed with a colorimetric kit based on the methodology for preparing digestion reagents analogous to the 5220D method proposed by the Standard Methods (APHA, 2012), approved by the USEPA. The COD digestion kits were prepared in 10 mL microtubes, containing 1.5 mL of digestion solution and 3.5 mL of catalyst reagent. For sample digestion, 2.5 mL aliquots of VWSE without treatment or after being treated (without dilution) were placed in these microtubes. Then, the microtubes were closed and placed in a digestion block (Merck, Spectroquant TR620), where they were heated at a temperature of 148 ºC for 2 h. After cooling for 30 min, the COD values were determined using a colorimeter with pre-programmed factory calibration in the concentration range of 25.0 to 1500 mg_{O2} L^{-1}.

The VWSE treated with the optimum condition obtained for the EC process was analyzed, before and after treatment, for metal content and other physical-chemical parameters, such as COD, BOD, thermotolerant and total coliforms, oils and greases (OG), pH and settleable solids. The metal content was also determined in the phases containing the floated compounds and the compounds settled at the bottom of the electrochemical reactor, resulting from the use of the EC treatment process in the most efficient experimental condition. These analyses were performed by laboratories accredited by the National Institute of Metrology, Quality and Technology (INMETRO-Brazil), following the methodologies established by EPA/2007 and SMWW 23rd edition.

2.3 VWSE treatment with the EC process

The VWSE treatment was carried out in a beaker, used as an electrochemical reactor containing 170 mL of effluent. The reactor was equipped with a pH measurement probe and another probe to measure the electrical conductivity of the VWSE. Two aluminum (Al) electrodes were set in parallel in the reactor with a distance of 2.0 cm between them, the working electrode (WE) and the counter electrode (CE).

All studies were carried out with aluminum electrodes (Al - alloy 1200 H14) prepared with dimensions of 15.00 cm x 1.50 cm x 0.03 cm. The surface of the electrodes was insulated with double-sided polyamide tape, with an exposed region revealing only a working surface area of 1.0 cm^2, for the electrochemical reactions.

The studies used the EC process operating potentiostatic, applying and keeping constant the values of electrical potential differences of 5.0 V, 7.5 V or 10 V. The treatment time was also evaluated, with values of 15, 30 and 45 min. For these operating processes, a complete factorial experimental design of type 32 was carried out to evaluate the effects of the electrical potential difference and the treatment time with the EC process on the percentage reduction of the COD, MBAS and turbidity values. Table 1 presents the levels and values used for each variable in the experimental design.

Table 1- Levels and values adopted for VWSE effluent treatment studies. Structure in accordance with the 3^2-type full factorial experimental design methodology.

Factors (variables)	Levels		
	-1	**0**	**+1**
Electric Potential Difference (V)	5.0	7.5	10.0
Time (min)	15	30	45

The percentage reduction values of COD, MBAS and turbidity, using the potentiostatic mode of the EC process, were analyzed in a normalized manner in relation to the respective values measured before the treatment experiments. This normalization was necessary due to the performance of several VWSE collections throughout the study. This procedure allowed for an adequate comparison of the percentage reduction values of the parameters throughout the treatment with the EC process, regardless of the initial variations in the respective measured values.

The percentage reduction values of the physical-chemical parameters of the effluents were analyzed based on the mean values, followed by the respective associated standard errors. The variations in the means were evaluated with statistical analyses using the analysis of variance (ANOVA) method and the Tukey test, with the objective of verifying the existence of significant differences generated with the different conditions of the EC process. The statistical analyses were performed considering a confidence level of 90.0% ($p<0.1$). In some analyses, it was possible to evaluate with 95.0% confidence ($p<0.05$). Statistical analyses were performed using Statistica® 7.0 software (StatSoft®, USA).

2.4 Evaluation of pH values of effluents treated with the EC process

The evaluation of the pH values of VWSE was performed by collecting aliquots of the effluent during the treatment process for 15, 30 and 45 min, in potentiostatic mode. In these studies, only the initial electrical conductivity value of VWSE was adjusted. The values were used to verify the final pH value of VWSE and to verify compliance with the relevant legislation in Brazil (CONSEMA 182), for the discharge of effluent into receiving water bodies and also to verify the formation of coagulant metallic species.

2.5 Kinetic study of the percentage reduction of COD, MBAS and VWSE turbidity during treatment with the EC process – potentiostatic mode

After defining the best experimental conditions in small electrochemical reactors, treatment experiments with the EC process were carried out on a larger scale, using a 2.0 L reactor and containing 1.6 L of VWSE. In this stage, Al electrodes (cathode and anode) were used, with a surface area of 18.0 cm^2 and a distance between the electrodes (DE) of 1.0 cm. The operating mode was potentiostatic, applying 10 V for a treatment time that varied from 0 to 180 min for the percentage reduction of COD, from 0 to 315 min for the reduction of MBAS and from 0 to 225 min for the percentage reduction of turbidity. In all experiments, the initial pH values of VWSE were adjusted to 5.5, 7.0 or 8.5, according to the experiment, by adding a 1 M NaOH or 1 M H_2SO_4 solution. The electrical conductivity values of VWSE were adjusted before EC treatment by adding 2.06 mL of a 1.0 mol L^{-1} NaCl solution (709.0 mg L^{-1} NaCl in solution) until the value of 900±100 µS cm^{-1} was set. The percentage reduction values of the physicochemical parameters were evaluated at specific times, from aliquots collected from VWSE during the EC treatments.

Additionally, a kinetic study of the percentage reduction values of MBAS was carried out, varying its initial concentration by adding a solution of anionic surfactants Linear Alkylbenzene Sulfonate (LAS) with a known concentration, prepared from the salt of this reagent, which was added to a known volume of real effluent with a concentration expressed in mg L^{-1} of MBAS, equal to 5.0 mg L^{-1}. Thus, it was decided to work with some concentration ranges whose values had already been measured in samples during other exploratory experiments in this research. The experiments were carried out in triplicate for concentrations of 61.6, 34.8 and 21.7 mg L^{-1} of MBAS in the VWSE. This stage of experiments was carried out after defining the best experimental condition in terms of pH within this study. From then on, the initial concentration of MBAS was monitored, which would cause some change in the kinetic profile of MBAS reduction in the reactor over 315 min.

2.6 Physicochemical characterization of VWSE treated with the optimal experimental condition of the EC process

The VWSE treated with the optimal condition of the EC process, which presented the greatest efficiency in reducing the COD, MBAS and Turbidity values, was stored in opaque polyethylene bottles containing 200 mL of sample and placed in boxes with ice for transport to the accredited laboratory for analysis. The COD analyses followed the methodology (PR-BLIII-022), the MBAS analyses followed the

methodology (PR-BLIII-086) and the turbidity analyses followed the SMWW 2130-B methodology. These samples were submitted to analysis at the Water and Effluent Analysis Laboratory (LANAE) of the Senai Institute of Environmental Technology, a laboratory certified by INMETRO/Brazil. The main objective was to validate the measured values of percentage reduction of these parameters and to add security to the information obtained in these studies.

3. Results and Discussion

3.1 Characterization of VWSE

The results of the physical-chemical characterization of VWSE before electrochemical treatment are presented in Table 2. The results are presented with mean values and respective associated error values.

Table 2 - Mean values for pH, temperature, electrical conductivity, COD, MBAS and Turbidity of VWSE before being treated with the EC process (mean±error).

pH	Temperature (ºC)	Electric Condutivity ($\mu S.cm^{-1}$)	COD ($mgo_2\ L^{-1}$)	MBAS ($mg\ L^{-1}$)	Turbidity (NTU)
9.1±1.5	24.3±1.0	597.8±69.0	697.0±55.0	41.5±15.8	652.9±207.7

The associated error values can be evaluated for each mean value. In particular, for turbidity, the variation in the mean value is 31.8% of the mean. This variation can be considered large, but it was expected because the samples were collected from different car wash stations and on different days. Each car wash station has its own specific characteristics, such as the chemical composition of the cleaning products and the number of vehicles washed per day. These different characteristics result in different compositions and concentrations of contaminants in the VWSE, providing large variations in the physicochemical parameters analyzed.

Regarding the pH value of the VWSE, it is possible that its alkaline character is due to the presence of surfactants, especially anionic surfactants present in detergents and cleaning products (Zhang et al., 2023). These anionic surfactants react with water and promote an increase in pH, due to the increase in the concentration of hydroxyl ions (OH^-). Recent studies have also highlighted the contribution of anionic surfactants in increasing the pH values of effluents with chemical compositions similar to the VWSE in question (Badmus et al., 2021; Zhang et al., 2023).

As for the electrical conductivity value of VWSE, it is in agreement with the literature, considering that the studies by Rubí-Juarez et al. (2015), Atiyah et al. (2019), El-Ashthoukhy et al. (2015) and Gönder et al. (2017) reported values between 796.0 and 1000 $\mu S\ cm^{-1}$ for similar effluents.

The mean COD value of VWSE is in agreement with those reported in scientific articles, being between 50 and 2050 $mgo_2\ L^{-1}$ for different VWSE, according to El-Ashtoukhy et al. (2015); Rubí-Juarez et al. (2015); (Silva et al. (2017); Krishina et al. (2017); Pandey and Takur (2017); Manilal et al. (2017); Rubí-Juarez et al. (2017);

Mohammadi et al. (2017); Gönder et al. (2019); Atiyah et al. (2019) and Torrens et al.(2026).

Regarding the value of the VWSE MBAS, they are similar to those reported by El-Ashthoukhy et al. (2015) and Gönder et al. (2017), who reported a concentration of 35 mg L^{-1}. Hashim et al. (2016) reported values between 51.5 and 56.5 mg L^{-1}, while Rubí-Juarez et al. (2015) reported 68.3 mg L^{-1}. In turn, Gönder et al. (2019) reported values of 290.0 mg L^{-1} of MBAS or 353.0 mg L^{-1} reported by Moulood & Abdoul-Majeed (2019).

The turbidity of VWSE is caused by the presence of solid debris in solution. In this study, the value of the turbidity of VWSE varied around a mean value equal to 652.9 ± 207.7 NTU. These values also agree with some values determined by Rubí-Juarez et al. (2015), Rubí-Juarez et al. (2017), Priya et al. (2019), Atiyah et al. (2019), Sravanth et al. (2019), who reported values between 180.0 and 925.0 NTU. In particular, in a study that involved the use of the EC process and also electro-Fenton, Mirshahghassemi et al. (2017) reported an initial value of 1400 NTU for VWSE.

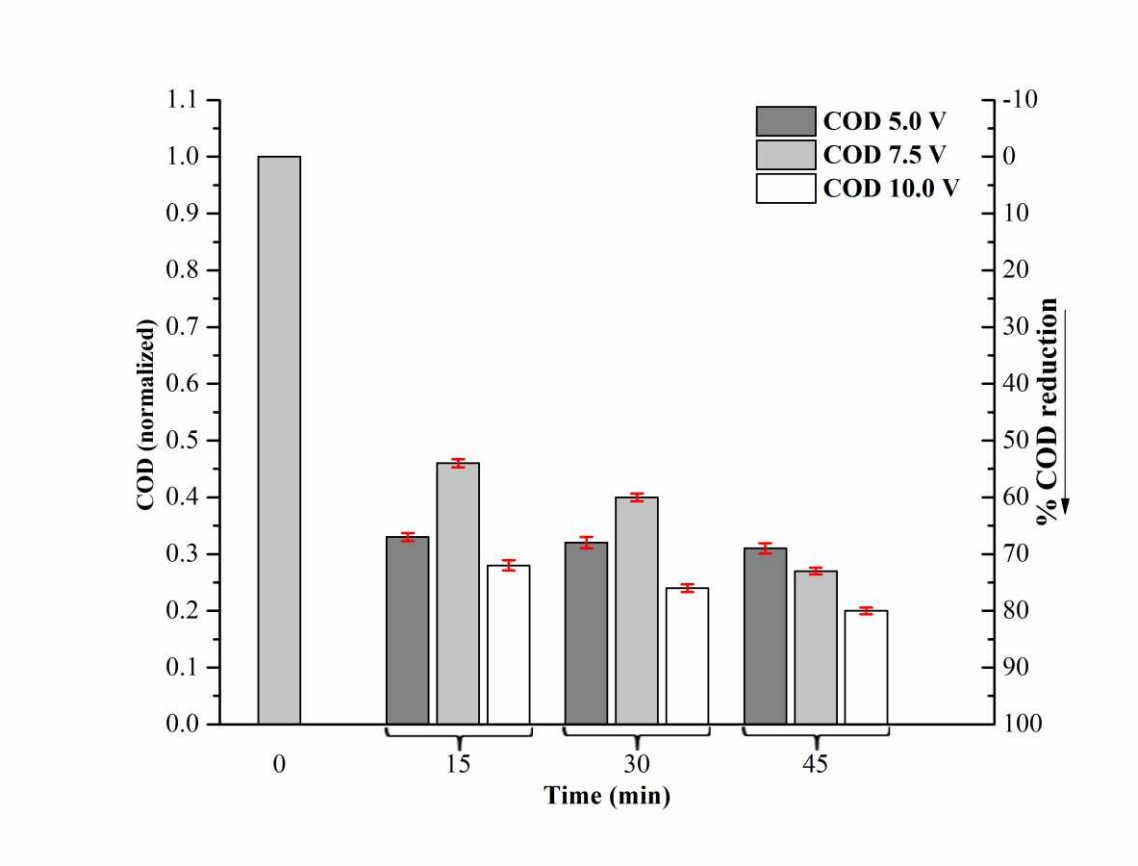
One finding regarding COD (Chemical Oxygen Demand) stands out as significantly different from the average ranges reported by other authors. In their study, the researchers report a wastewater sample (VWSE) with an initial (raw) COD of 5,752.0 mgo_2 L^{-1}, a turbidity of 520 NTU, and an OGs content of 210.0 mg L^{-1}. The experiments were conducted in a batch electrochemical cell, using a 0.5 L cylindrical glass reactor. Two flat, rectangular stainless steel plates served as the anode and cathode, measuring 9.0×3.0×0.2 cm (length × width × thickness), with an inter-electrode distance (IED) of 3.0 cm. The effective surface area of the anode was 54.0 cm^2. The experimental results showed an 89.8% reduction in COD at a pH of 9.0, with an applied electric current of 2.0 A over a duration of 27.5 min (Madih, K., Sayed et al. 2026).

These values indicate that VWSE has a high organic load, high MBAS and turbidity values, which can be attributed to the presence of polluting substances, such as surfactants and other chemical compounds from detergents and cleaning products used to wash vehicles, and solid particles in suspension, which can be harmful to the environment if discarded without proper treatment.

3.2 COD values of VWSE treated with the EC process in potentiostatic mode

The COD values of VWSE and the percentage reduction of these values after treatment with the EC process, in potentiostatic mode using Al electrodes are presented in Figure 1, where the normalized COD axis represents the initial value of the effluent and the COD reduction percentage axis represents the reduction value at the end of each experiment. These values are presented for different treatment times and for different values of electrical potentials.

Figure 1 - COD value and percentage reduction of COD determined for VWSE before and after treatment with the EC process for 15, 30 and 45 min, applying electrical potential of 5.0 V, 7.5 V and 10.0 V, with Al electrodes.



The results indicate that in the first 15 min of treatment there is a significant reduction in the COD value of VWSE, reducing the value between 55.0% and 73.0% for the three electrical potentials applied. After 30 min of treatment, the reduction was from 60.0% to 77.0% and after 45 min of treatment the reduction was between 69.0% and 80.0%. In the condition after 45 min the absolute COD values were 200.7±10.0 $mgo_2\ L^{-1}$, 174.0±6.6 $mgo_2\ L^{-1}$ and 132.7±7.2 $mgo_2\ L^{-1}$, for the electrical potentials of 5.0 V, 7.5 V and 10.0 V, respectively.

From the ANOVA statistical analysis, with a confidence limit of 90.0%, the electrical potential and treatment time significantly influenced the reduction of the COD of the VWSE with the EC process, with the potentiostatic operating mode and with the Al electrodes.

Regarding the different electrical potentials applied in the treatment, it is observed that with the highest value (10.0 V) the greatest percentage reduction of COD occurs. It is expected that with the increase in the electrical potential the amount of electrical energy available for oxidation of the Al electrode and the greater the amount of Al ionic species generated in a given time interval, which results in a higher oxidation and flotation rate of the organic compounds present in the VWSE, which are responsible for the COD values.

Regarding the reproducibility of the experiments, the determined COD values under the different treatment conditions showed a coefficient of variation (RSD) between 0.5% and 5.6% in relation to the mean value of the measurements. This RSD range indicates good accuracy in the execution of the experiments and in the COD

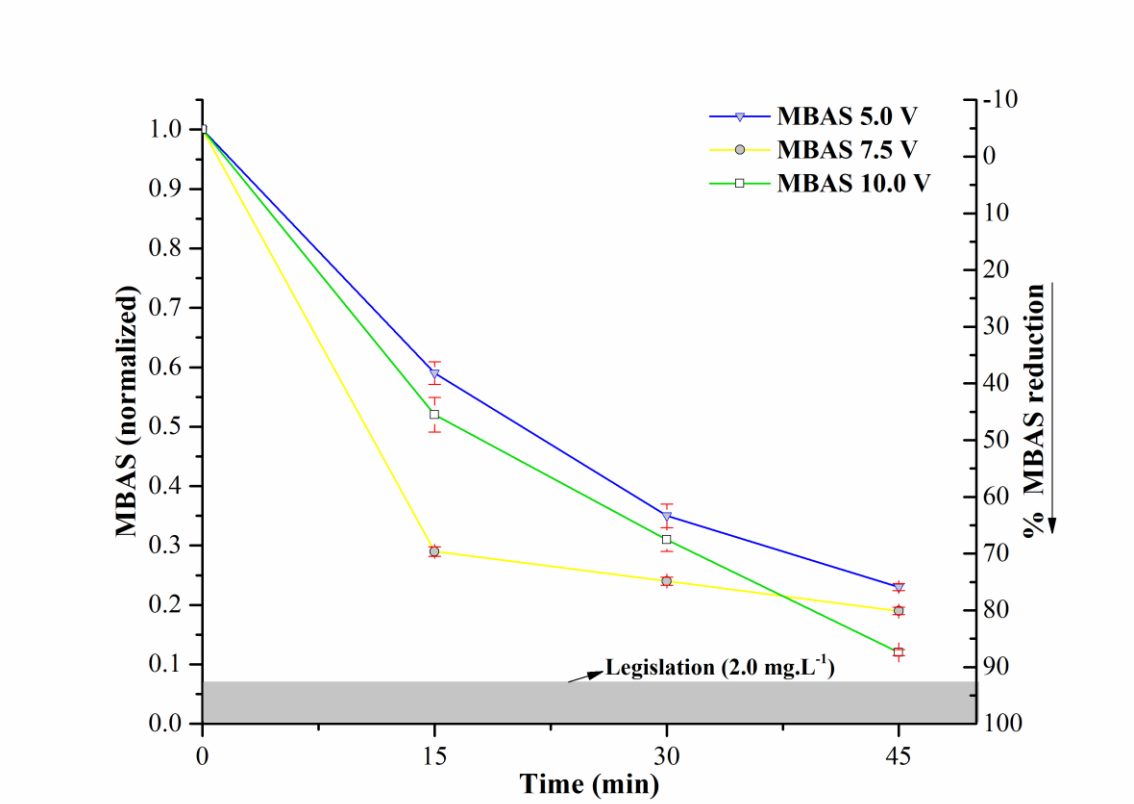
measurements. When comparing the results obtained with results reported in other studies, it is observed that the mean value of percentage reduction in COD is lower. The authors Atiyah and Abdul Majeed (2019a, b) obtained efficiencies of 95.0%-98.0% with the application of an electrical potential of 30.0 V for 90 min in the VWSE treatment, with COD values between 632.0 and 2032 mgo_2 L^{-1} in the raw effluent. In a similar study, Sravanth et al. (2020) obtained a 92.0% reduction in the COD of locomotive wash effluent, using EC treatment with an electrical potential of 28.0 V for 60 min and with initial COD values between 3400 and 3840 mgo_2 L^{-1}. It is important to emphasize that in these studies the electrical potentials and treatment times used were 2 to 3 times higher, compared to those employed in this study.

The EC treatments using Al electrodes demonstrated good efficiency in reducing the COD values of VWSE, with treatment times of up to 45 min and with different electrical potential values, up to 10.0 V. The use of relatively low potentials and short time intervals presents additional advantages, especially because they provide lower energy losses due to the Joule effect in the electrolytes.

3.3 MBAS values of VWSE treated with the EC process in potentiostatic mode

The MBAS values of VWSE and the percentage reduction of these values after treatment with the EC process, in potentiostatic mode using Al electrodes, are presented in Figure 2 where the values on the normalized MBAS axis represent the initial value and the MBAS reduction percentage axis represents the reduction value at the end of each experiment, as well as the limit established by legislation (resolution 182/21 CONSEMA/SC). These values are presented for different treatment times and for different electrical potential values.

Figure 2 – MBAS value and percentage reduction of MBAS determined for VWSE before and after EC treatment for 15, 30 and 45 min, applying electrical potential, 5.0 V, 7.5 V and 10.0 V, with Al electrodes and comparison with Consema/SC legislation number 181/2021



Regarding the efficiency of the EC process in reducing the MBAS parameter values, it is possible to observe that in the initial 15 min there is a significant reduction of approximately 41.0% when treated with 5.0 V and 71.0% when treated with 10.0 V. The efficiency increases to 65.0% and 76.0% after 30 min and to 75.0% and 88.0% after 45 min, respectively. Even applying the greatest difference in electrical potential and the longest treatment time (10.0 V and 45 min), the final mean concentration of MBAS is 4.4±0.3 mg L^{-1}, representing a reduction efficiency of 88.0% in relation to the initial concentration determined in the VWSE (Table 2). However, this value still does not meet the limit allowed by resolution 181/2021 of CONSEMA/SC for the release of effluents.

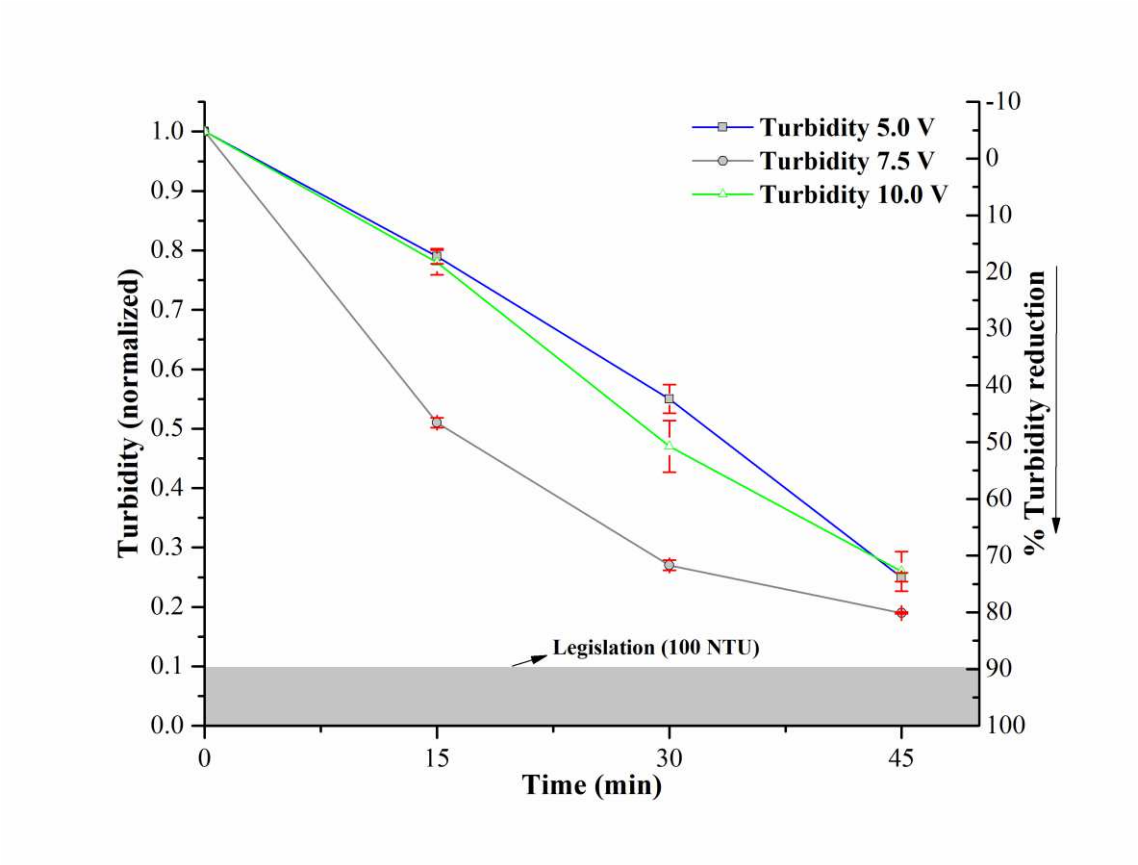
These results are quite promising, as they demonstrate the high efficiency of the EC process in reducing MBAS values. In these experiments, RSD values ranged from 2.0% to 11.1%, which demonstrates the reliability of the results obtained, since for MBAS analysis, the standard method recommended by Standard Methods reports accepted RSD values in the range of 24.0%.

Observing the results of reducing MBAS values with the EC process with Al electrodes, it is possible to see that in none of the treatments did the MBAS concentration reach values below or equal to the maximum limits allowed by Consema Resolution number 181/2021 of Santa Catarina (SC), which is 2.0 mg L^{-1}. This indicates that applying EC within the limits for the values of the variables studied, the MBAS levels still exceed the standards established by legislation for effluent disposal after treatment.

3.4 Values for VWSE turbidity after treatment with the EC process operating in potentiostatic mode

The VWSE turbidity values and the percentage reduction of these values after treatment with the EC process, in potentiostatic mode using Al electrodes, are presented in Figure 3 where the values on the normalized turbidity axis represent the initial value and the axis of the percentage of turbidity reduction represents the reduction value at the end of each experiment as well as the limit established by legislation (CONAMA 430/11). These values are presented for different treatment times and for different values of electrical potentials.

Figure 3 – Turbidity value and percentage reduction of Turbidity determined for VWSE before and after EC treatment for 15, 30 and 45 min, applying electrical potential, 5.0 V, 7.5 V and 10.0 V, with Al electrodes and comparison with CONAMA 430/11 legislation



The results presented in Figure 3 show that with 45 min of treatment it is possible to reduce turbidity by 88% using the highest value of electric potential difference, 10.0 V. With lower values, 5.0 V and 7.5 V, the turbidity reduction is 75.0% and 82.0%, respectively.

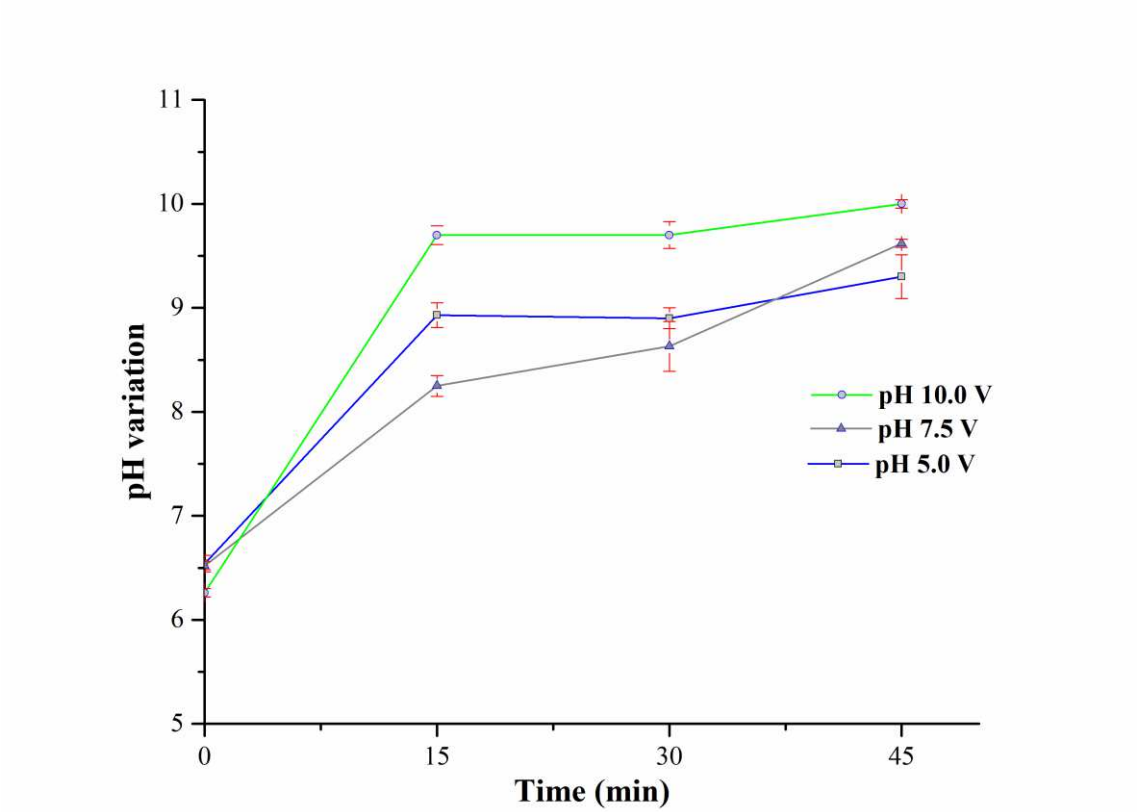
These results indicate a greater efficiency of turbidity reduction with higher values of electric potential. This result is expected, since turbidity is directly related to the amount of suspended sediments in the medium, in addition to other characteristics

such as the size and shape of particles, bacteria and germs (Sahoo & Anandhi, 2023; Matos et al., 2024). With higher values of electrical potential, it is expected that the oxidation rate of Al electrodes will be higher and larger quantities of flakes will be generated in the same time interval, which favors the reduction of larger quantities of pollutant particles in the medium and the reduction of turbidity (Cañizares et al., 2007, 2005; Mouedhen et al., 2008; Jiménez et al., 2012).

3.5 Evolution of pH during VWSE treatments with EC process in potentiostatic mode

During the VWSE treatment experiments with Al electrodes, pH values were monitored. Figure 4 shows the mean pH values of VWSE during the treatment up to 45 min of EC with electric potential difference values of 5.0 V, 7.5 V and 10.0 V.

Figure 4 - pH values of VWSE without and with EC treatment applying electrical potential of 5.0 V, 7.5 V and 10.0 V, with Al electrodes



In the first 15 min of treatment, the pH increases rapidly to basic values. With the highest electrical potential of 10.0 V, in 15 min the mean pH value is 9.8, an increase of 51% in relation to the pH value of VWSE without treatment. After 15 min, the pH values show small variations, tending to a mean value of 10.0 with the treatment

with the electrical potential of 10.0 V and pH of 9.0 with the treatment using the electrical potentials of 5.0 V and 7.5 V.

The increase in the pH of VWSE can be related to the oxidation reactions of the metallic Al constituent of the cathode and the reduction of the hydrogen species present in the electrolyte, at the anode. As a consequence, the H^+ species are consumed by the anode and the pH in VWSE increases. At the same time, the hydroxyls (OH^-) react with the Al^{3+} species generated by the oxidation of the anode, resulting in the formation of aluminum hydroxide ($Al(OH)_3$).

The Pourbaix diagram for Al dissolution shows that in media with pH values between 4.0 and 9.5, the predominant species in solution are $Al(OH)_3$ and Al_2O_3 (Jiménez et al., 2012). Therefore, it is very likely that during the VWSE treatment for 45 min with electrical potentials of 5.0 V, 7.5 V and 10.0 V, the main species formed are $Al(OH)_3$ and Al_2O_3, according to the Pourbaix diagram (Jiménez et al., 2012; Ingelsson; Yasri; Roberts, 2020) for Al. The greater increase in pH under the condition of higher electrical potential is related to the greater availability of energy for the Al oxidation and hydrogen reduction reactions at the cathode, which results in a higher rate of reduction of H^+ species at the cathode and the generation of greater amounts of $Al(OH)_3$ and Al_2O_3.

The COD reduction results obtained in this study and the relationship with the pH of the medium are in agreement with that described by Linares-Hernández et al. (2009), who also observed that pHs between 4.0 and 8.0 were more efficient in reducing COD during 60 min of treatment compared to pHs 2.0 or higher than 9.5. However, the authors point out that within the pH range between 4.0 and 8.0, the effect of pH on COD reduction is not significant, considering the specific conditions of the experiment.

In the study by Rafiee et al. (2020), in which they used landfill leachate for the EC process in galvanostatic mode, a linear relationship was observed between the increase in pH and the increase in electric current density in the medium, within the range of 22.0 mA cm^{-2}, which is explained by Faraday's law. The authors observed that at acidic pH, $Al(OH)_3$ complexes predominate, which are insoluble, whereas at basic pH, these complexes become more soluble. The best flakes were formed at pH 5.2-8.8, where only $Al(OH)_3$ is insoluble. Therefore, according to this study, the best results for COD reduction were obtained at more acidic pH.

The Al dissolution and release process during EC was studied by Jiménez et al. (2012), where the authors analyzed the Al speciation at different pHs and electric current densities (galvanostatic mode). The authors identified that at acidic pHs, monomeric and polymeric species are formed, with little formation of $Al(OH)_3$ precipitates. In conditions where the pH was close to neutrality (5.0-9.0), the $Al(OH)_3$ precipitates were primary species with few soluble species at electric current densities of 20.0 mA cm^{-2}. At electric current densities between 30.0 and 50.0 mA cm^{-2}, the formation of soluble $Al(OH)_3$ species increased (80.0%-100% of the species in solution). At pHs above 9.0, there was a decrease in precipitate formation, increasing the proportion of monomeric and polymeric Al at all electric current densities studied (20.0-50.0 mA cm^{-2}). The study demonstrated that the application of electric current

density from 20.0 mA.cm^{-2} promotes a more expressive increase in the amount of $Al(OH)_3$ and its stability in solution.

The results of the present study are consistent with these studies. As illustrated in Figure 4, the pH increased in the first 15 min of EC, then the pH reached a stable level, especially in the pH region of 9.0 with the highest electric potential (10.0 V), which will result in a higher current density. This increase in current density can lead to a greater amount of $Al(OH)_3$ in solution, which can contribute to the efficient reduction of contaminants in the solution studied.

3.6 Compilation of the EC process conditions that presented the best results in the treatment of VWSE

In order to compile the best results of the EC process efficiency, the experimental condition that provided the greatest efficiency in the treatment was defined. The best experimental condition for the EC process was obtained after 45 min of treatment using an electric potential of 10.0 V. Table 3 presents the final values of the turbidity concentration, MBAS, COD and pH of the effluent, corresponding to triplicates of the post-treatment experiments by EC using the Al electrodes. The maximum limits established by some legislations were also included for reference. These results were compared statistically using the Tukey test ($p<0.05$), considering the means for each electrode, electric potential and electric current density applied.

Table 3- Real values (not normalized) of turbidity, MBAS, COD and final pH after EC treatment in potentiostatic mode with Al electrodes, (mean±SD) and limits allowed by some legislations

	Turbidity (NTU)	**MBAS (mg L^{-1})**	**DQO (mgo$_2$ L^{-1})**	**pH$_{final}$**
	[1]100[#];	[2]2.0	[3]210;	[1]5.0-9.0 [2]6.0,-9.0
Al 10 v	94±21.2[a]	4.41±0.3[a]	133±7.2[a]	10.0±0.6[a]

[#]Class waters 2 e 3;
[1]CONAMA 430/11; [2]CONSEMA SC 181/21 and [3]CONSEMA SC182/21

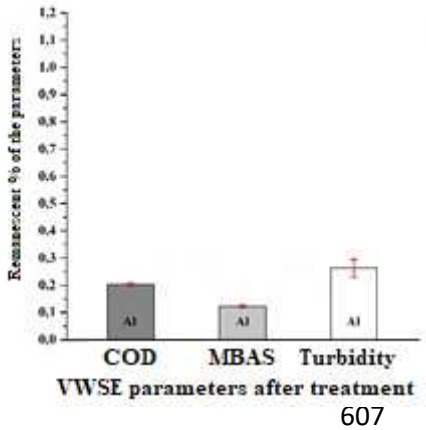
When comparing the concentration data of the parameters measured after the different EC treatments presented in Table 3 with the standard discharge values established by different legislation, it is observed that some of these values still limit the possibility of disposing of this effluent. Although the COD concentration after the EC treatment using Al electrodes in potentiostatic mode complies with the discharge standards, it was not as effective for MBAS, in addition to presenting an increase in pH. These results indicate the need to make adjustments and investigate the EC process conditions in more detail, aiming to achieve the established discharge standards.

The results presented in Table 3 reveal, through the analysis of the Tukey test ($p<0.05$), statistically significant differences between the two treatments for the Turbidity, MBAS and COD parameters. It is also observed that the Al electrodes, using the potentiostatic operating mode, presented more promising results, mainly for the

reduction of COD and turbidity and slightly less so for MBAS. These results demonstrate a greater tendency to reduce these parameters with the use of Al electrodes in potentiostatic mode, where the loss of electrode mass is lower during the EC process.

To better visualize the difference in the values of the COD, MBAS and turbidity parameters, the data presented in Table 3 were normalized based on the raw VWSE values and are represented in Figure 11, in terms of remaining percentage.

Figure 11 - Remaining percentage of parameters in VWSE after EC treatment with Al electrodes after applying the electrical potential of 10.0 V for 45 min

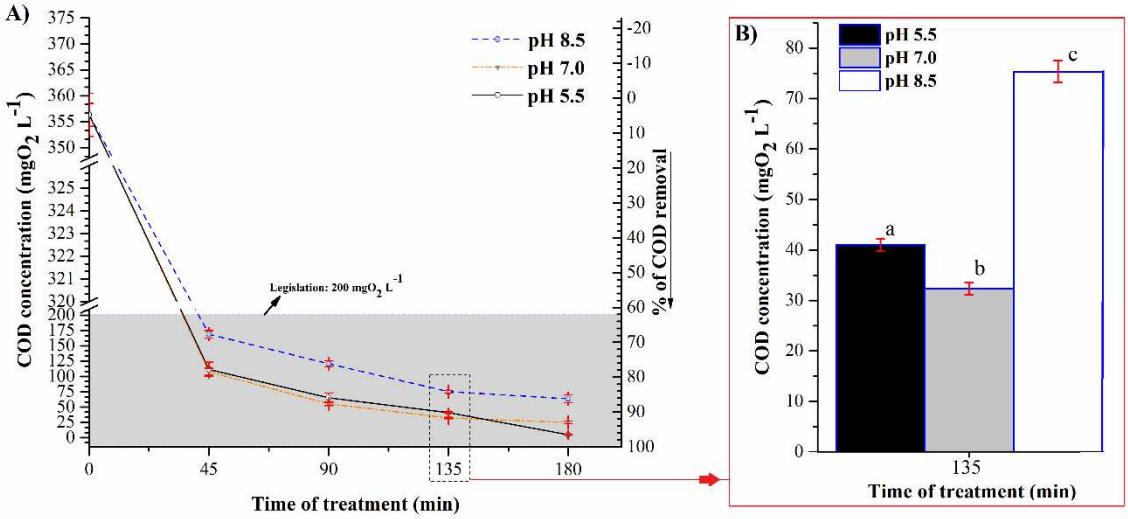


Based on the results obtained for the 170 mL reactors and the statistical analysis performed, it is possible to state that the treatment of VWSE by EC using Al electrodes in reactors operating in potentiostatic mode is a viable option. This system showed good efficiency in reducing the parameters analyzed and a lower consumption of electrode mass during treatment. Therefore, for subsequent studies, the VWSE treatment was performed using the potentiostatic mode with Al electrodes.

3.7 Results of the kinetic study of the reduction of COD, MBAS and turbidity during the EC treatment in potentiostatic mode with Al electrode

Based on the data obtained for the 170.0 mL reactors, the kinetic studies of this stage were conducted using a reactor with a volume of 1.6 L and raw VWSE, which presented 361.0 mgo_2 L^{-1} of COD, 60.1 mg L^{-1} of MBAS and turbidity equal to 284 NTU. The objective of this study stage was to identify the kinetic behavior of the electrochemical treatment process and determine the best pH condition and treatment time to be applied in a reactor with a view to reducing the COD, MBAS and turbidity parameters to reach values below those established by current legislation. Figures 12A and 12B present the results obtained in these kinetic studies for the COD parameter. Figure 12(a) presents the kinetics of COD concentration reduction over up to 180 min of EC treatment applying a fixed electric potential of 10.0 V, as well as the reduction percentage. Three initial VWSE pH values were evaluated: 5.5, 7.0 and 8.5. Figure 12(b) highlights the statistical difference, making a cut of the data for the time of 135 min.

Figure 12– (a) Kinetics of COD concentration reduction as a function of treatment time by EC with Al electrode, applying an electric potential of 10.0 V, varying the initial pH of 5.5, 7.0 and 8.5, and the respective percentage of COD reduction. (b) COD values at 135 min, with statistical analysis (Tukey test, $p<0.05$)

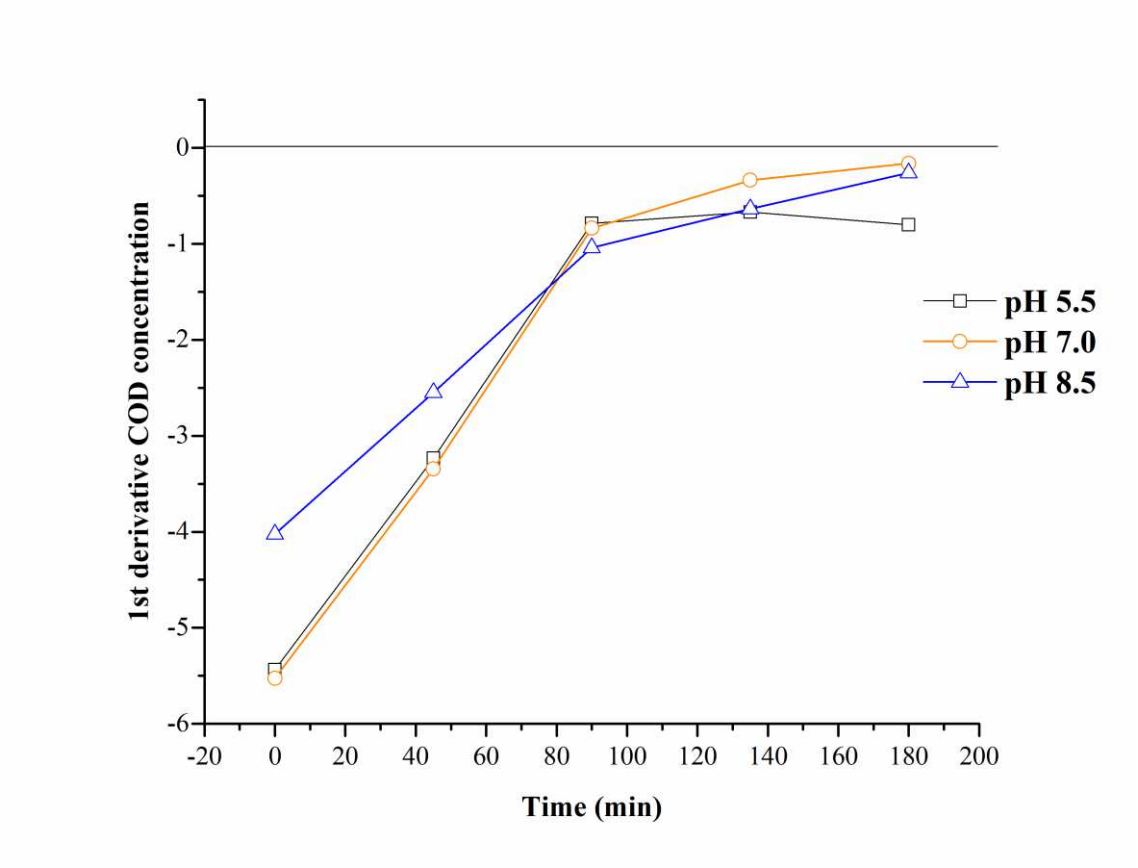


* Different letters between the bars mean that the values differ from each other, Tukey ($p>0.05$).

Figure 12(a) shows that pHs 5.5 and 7.0 resulted in greater reductions in COD concentration. In all pH ranges evaluated, the COD concentration was below 210 mgo_2 L^{-1}, a value stipulated for the years 2023-2030 by resolution 182/2021 CONSEMA/SC of Brazil, for systems with effluent discharge of less than 5 L/S (Consema, 2021). It is also worth highlighting, as observed in this figure, that through the analysis of the results at different times, such as at 135 min, it indicates that the initial pH adopted has a statistically significant effect on the reduction of COD. It is noteworthy that the more acidic the initial pH, the greater the reduction in COD over the 180 min of treatment, confirming a positive effect of pH in reducing this parameter. This behavior was expected, as already mentioned in this study, because in an acidic environment there is a greater release of aluminum ions (Al^{3+}) from the Al electrodes, thus increasing their availability for coagulation reactions to occur, aiding in the reduction of particles and organic compounds present in the effluent. In addition, pH influences the solubility of metal hydroxides, regulates the conductivity and zeta potential of the solution in wastewater, facilitating the transfer of electrical charge during the electrochemical process (Naje et al., 2016; Sahu et al., 2014). This results in greater efficiency in the oxidation of organic compounds and in the reduction of COD.

Figure 13 presents the data obtained for the values of the first derivative of the COD concentration in the VWSE throughout the EC process, which consequently allows us to observe the reduction rate (concentration/time).

Figure 13 – Derivative of COD concentration as a function of EC treatment time applying an electrical potential of 10.0 V in VWSE treatments with initial pH of 5.5, 7.0 and 8.5

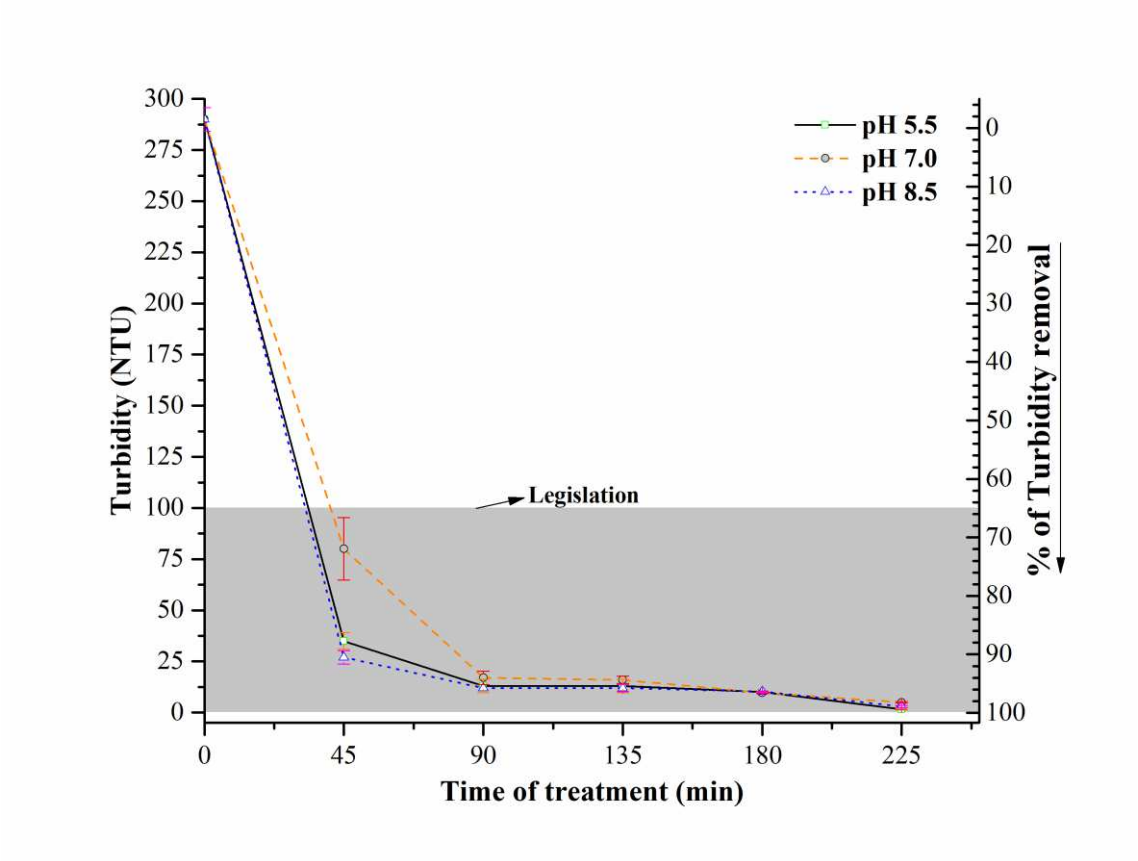


The COD reduction rate over time, illustrated in Figure 13, was represented by the concentration derivative. It can be observed that for pH 5.5, the reduction rate begins to stabilize after 135 min of EC treatment, followed by a slight decrease at 180 min. On the other hand, for pHs 7.0 and 8.5, it is possible to observe an opposite behavior, indicating that the COD reduction in these two higher pH conditions requires a longer time to reach lower values of this contaminant. The COD concentration at the end of 180 min of treatment was 5.3 $mgo_2\ L^{-1}$, 25.0 $mgo_2\ L^{-1}$ and 63.6 $mgo_2\ L^{-1}$ for pH 5.5, 7.0 and 8.5, respectively. This profile confirms that only with a longer treatment time can higher COD reduction percentages be obtained at neutral or alkaline pHs, such as 7.0 and 8.5. Furthermore, the stability shown for the reduction rate at pH 5.5 demonstrates nothing more than a small concentration of COD remaining in solution. This proves that if there are far fewer contaminant compounds available for reactions with the hydroxypolymers formed, the number of reactions will be lower, and consequently the reaction rate will be lower. Even when comparing pHs 5.5 and 7.0, there comes a time when the reactions are not favored and the rate between them differs, demonstrating the importance of studying pH. This statement becomes much more evident when observing the start of the EC process from pH 8.5, when the slope of the line representing the rate is completely different from the others.

Figures 14 and 16 present the kinetic results, under the same conditions as Figure 12(a), for turbidity and MBAS concentration, respectively. However, for these cases, a larger interval of time data is presented. It is also worth noting that, like Figure

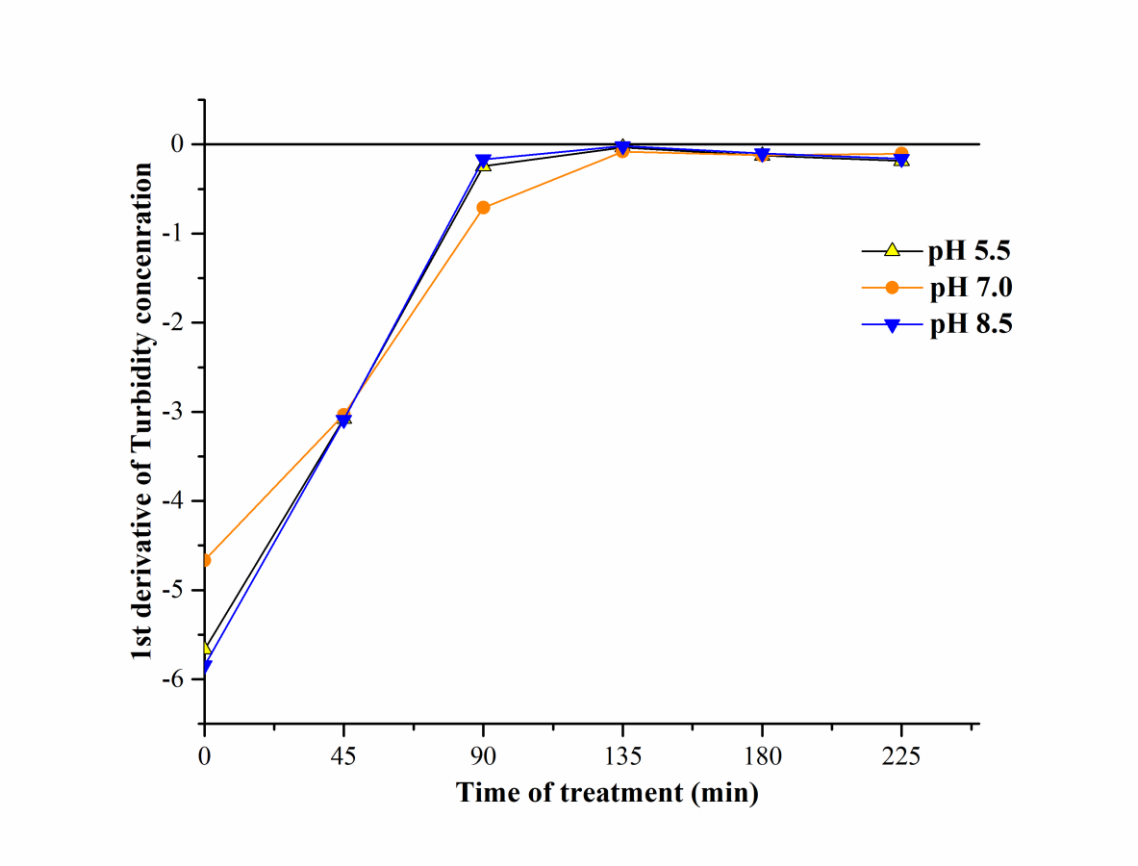
13, Figures 15 and 17 present data on the derivative of turbidity and MBAS concentration as a function of time for the same initial pH values of VWSE, respectively. Figures 15 and 17, which illustrate the derivatives, allow us to observe that there is a reduction rate (concentration/time), and this rate tends to decrease as the concentration of the species available in solution becomes lower.

Figure 14 – Kinetics of reduction of turbidity concentration during 225 min of EC treatment with Al electrode, applying electric potential of 10.0 varying the initial pH of 5.5, 7.0 and 8.5 and the respective percentage of turbidity reduction



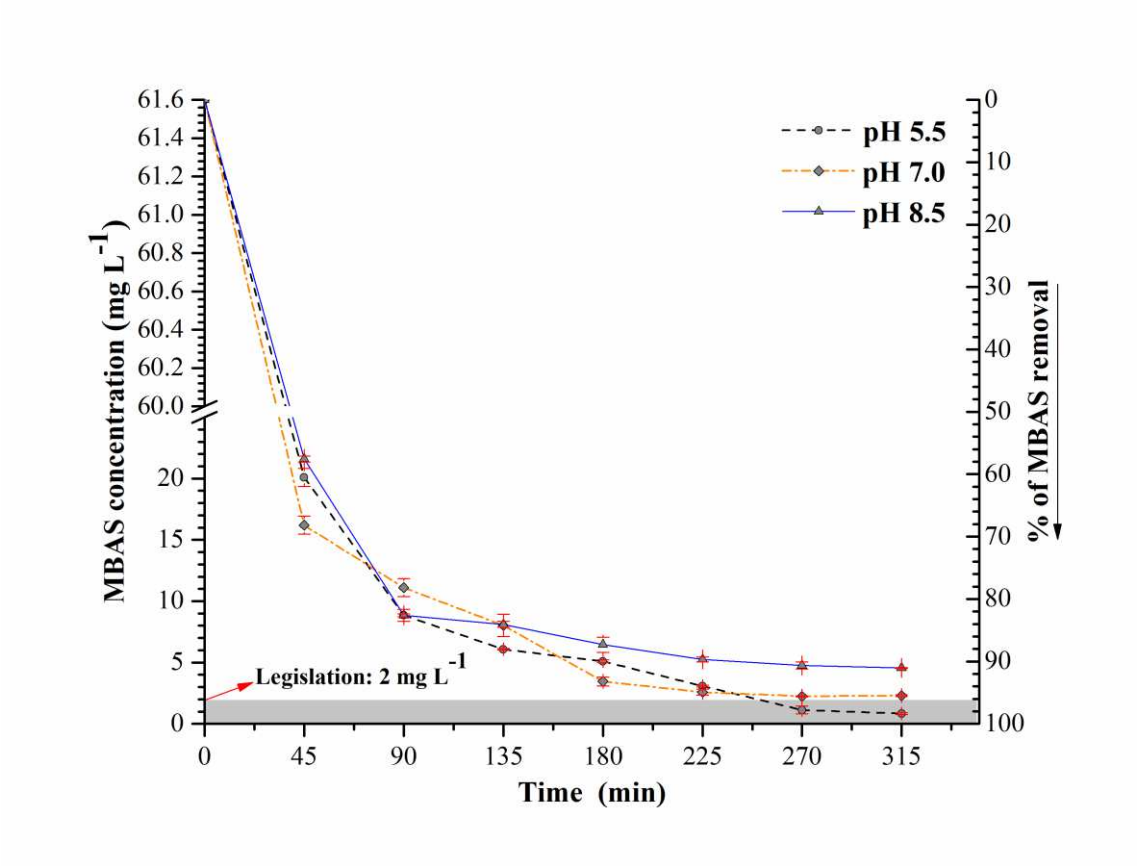
For the turbidity parameter in the VWSE, Figure 14, it is possible to observe that the reduction occurs mainly in the first 45 min of EC for pH conditions of 5.5 and 7.0. At 90 min, the turbidity reduction exceeds 90.0% in all pH conditions evaluated. And at the end of 225 min of treatment, the turbidity varied between 1.0 and 5.0 NTU for all conditions. The final turbidity values in the treated VWSE represent that after 45 min under the conditions studied, the VWSE meets the requirements determined by the National Environmental Council (CONAMA) 430/2011 for turbidity.

Figure 15 - Derivative of turbidity concentration as a function of treatment time applying an electrical potential of 10.0 V in VWSE treatments with initial pH of 5.5, 7.0 and 8.5



Through the analysis of the data obtained by the derivative presented in Figure 15, a very high similarity was observed between the data for pH 7.0 and 8.5 for the turbidity reduction rate and the values overlap throughout the studied interval. For pH 5.5 this rate was a little different at the beginning, but from 135 min onwards, the data practically matched the others obtained. This corroborates what was previously said in relation to the availability of species in solution, since in all the initial pH conditions adopted, from 135 min onwards, the reduction rate becomes small and the continuity of the EC process would only be interesting from the point of view of water reuse for more noble purposes in relation to this parameter.

Figure 16- Kinetics of MBAS concentration reduction as a function of time, during 315 min of EC, applying an electrical potential of 10.0 varying the initial pH of 5.5, 7.0 and 8.5 and the respective percentage of MBAS reduction in comparison with the limit of Resolution 181/21 of Consema/SC

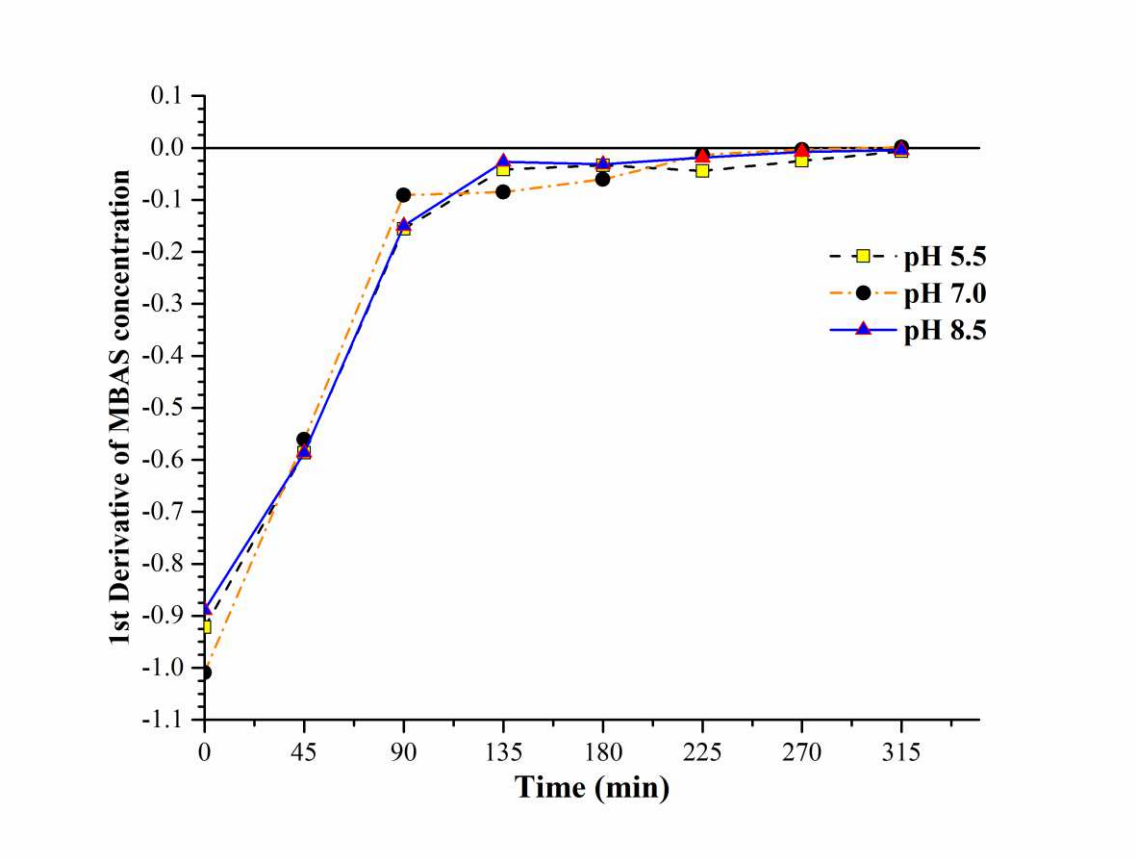


The reduction of MBAS during the EC treatment time was evaluated for different initial pHs, as shown in Figure 16. In the first 90 min of treatment, a significant reduction of 80.0%-87.0% of the initial MBAS concentration was observed for the different initial pHs evaluated. This indicates an initially high reduction rate that progressively decreases over time. In the 270-315 min conditions, the reduction efficiency was 96.0%-98.0% of MBAS, with a greater reduction again being observed at a more acidic pH. Therefore, the results obtained meet the limits established by the Brazilian CONSEMA/SC legislation (2.0 mg L^{-1}) with a treatment time equal to or greater than 270 min of EC at pH 5.5, resulting in concentrations equal to or less than 2.0 mg L^{-1} of MBAS.

In a study involving a synthetic MBAS sample, Villabona-Ortiz et al. (2021) prepared a solution containing 186 mg L^{-1} of MBAS and evaluated the effects of electric potential (10.0-20.0 V), treatment time (0-60 min), DE (1.0-2.0 cm) and electrode material (Al or Fe). The authors obtained 65% and 75.1% reduction of MBAS after 20 and 60 min of treatment, respectively, applying an electric potential of 20.0 V with DE of 1.5 cm and Al electrodes. It was also observed that increasing the treatment time reduced the reduction efficiency due to lower contaminant availability, which resulted in less formation of clots capable of trapping or adsorbing contaminants. Results of greater efficiency with longer treatment time and at acidic pH with Al electrodes were also obtained by Mohebrad et al. (2017), when they evaluated the reduction of MBAS with different electrodes at pH 3.0-9.0.

Regarding the MBAS reduction rate over time, shown in Figure 17, it is observed that from 135 min onwards the reduction rate assumes a plateau that tends to be constant. It is observed that the reduction rate is slower in relation to the treatment time, requiring longer treatment times per EC, such as 270-315 min. Comparatively, the treatments at pH 7.0 and 8.5 presented reduction rates that were still increasing, although at a slower pace in the interval between 135 and 315 min, compared to the treatment at pH 5.5.

Figure 17- Derivative of MBAS concentration as a function of time, during 315 min of treatment applying 10.0 V in VWSE treatments with initial pH of 5.5, 7.0 and 8.5



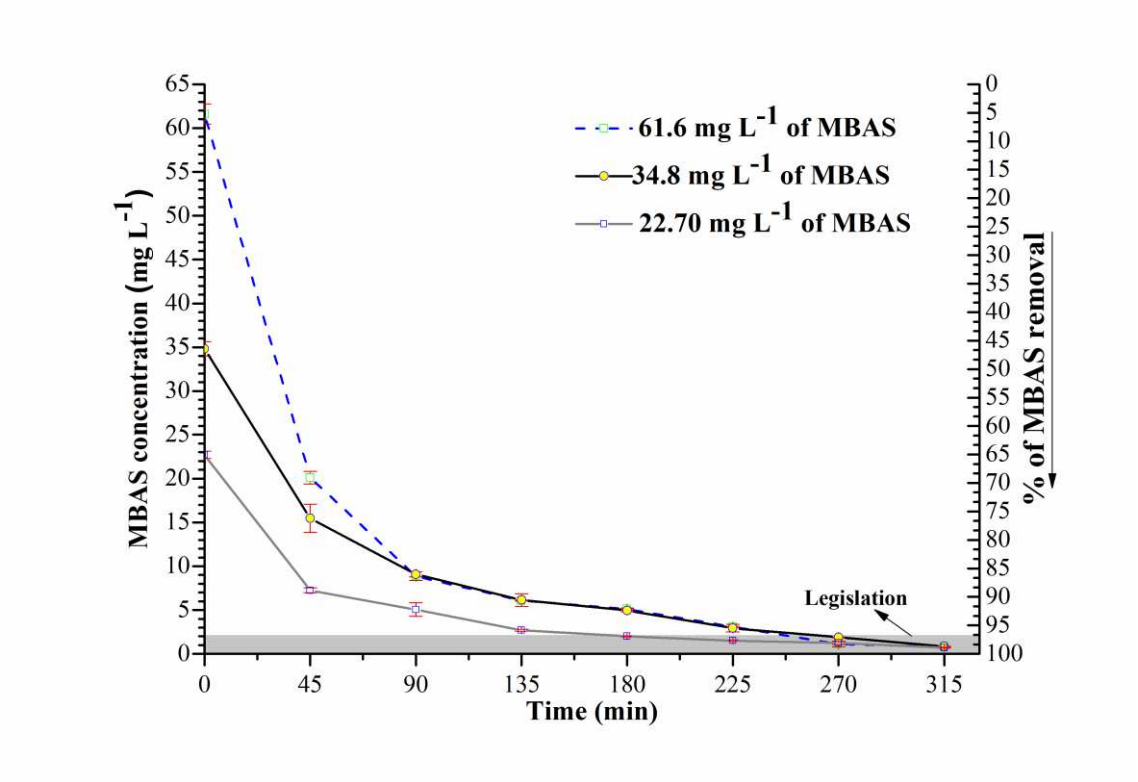
Considering the results obtained in this study and the high initial concentration of MBAS, this parameter, compared to the others, proved to be critical in the proposed EC process for its reduction in VWSE. In this sense, a new study was carried out with different concentrations of MBAS in an EC treatment time between 0 and 315 min, maintaining the pH at 5.5, which in general proved to be the most efficient pH range in reducing COD, turbidity and MBAS. Thus, a new batch of treatments was carried out, using three new VWSE samples with initial MBAS concentrations equal to 22.0 mg L^{-1}, 34.8 mg L^{-1} and 61.6 mg L^{-1}, respectively. These samples were collected on different days at the wash stations, precisely considering the days with the highest or lowest load of surfactant products added to remove dirt from the vehicles.

For this evaluation, the results of the MBAS reduction kinetics are illustrated in Figure 18 together with the MBAS reduction percentage. Figure 18 shows the study of

the decay of MBAS concentration as a function of time for conditions of different initial concentrations of this contaminant, for an initial pH of 5.5 with application of an electric potential of 10.0 V.

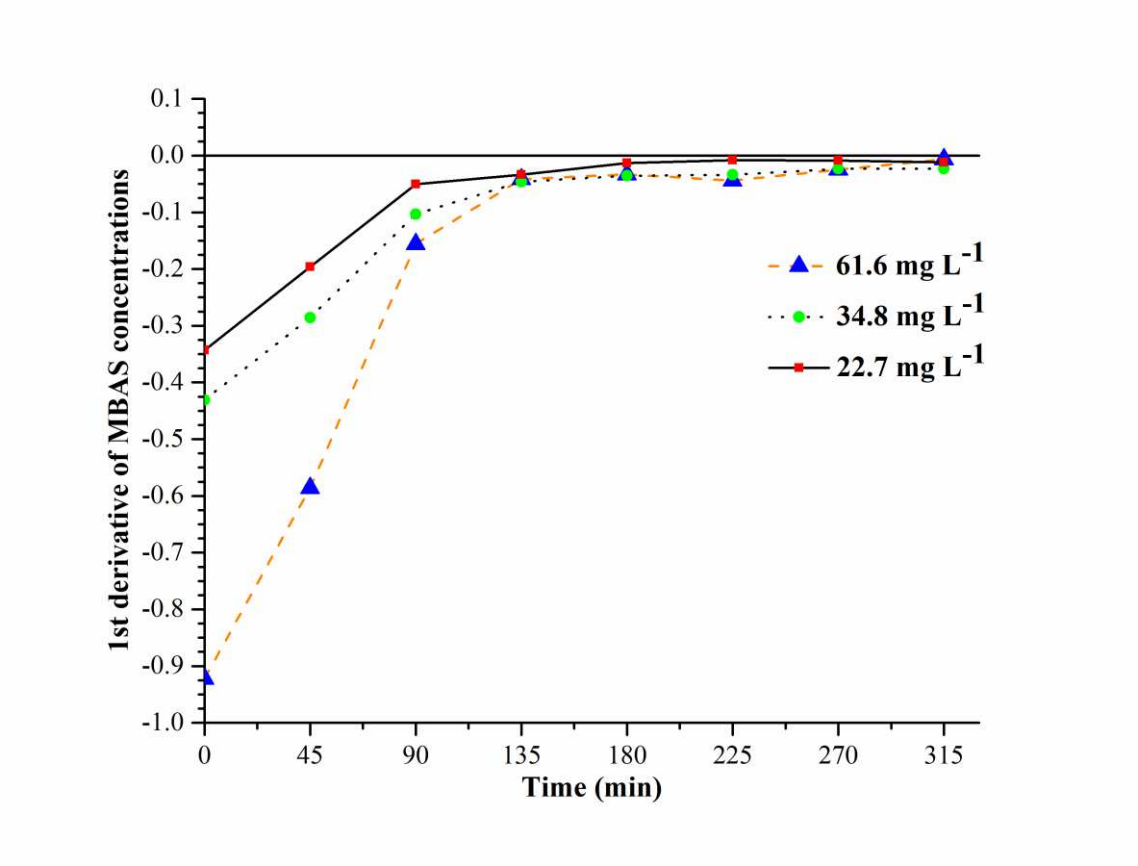
The results presented in Figure 18 show an initial behavior of the reduction rate in the first 90 min of EC, and the kinetics of the treatment were similar for the three concentrations evaluated, indicating that regardless of the initial concentration, the reduction rate is high at the beginning of the process and decreases throughout the treatment. This behavior was observed in the kinetic profile of the three concentrations. It was observed that after 270 min of EC, the final concentration of MBAS varied between 0.85 and 2.0 mg L^{-1} in the three cases evaluated, with reduction efficiency between 92.0% and 97.0%. In addition, it was found that the reduction rate decreased slightly when the initial concentration of MBAS was higher for the same EC time interval evaluated.

Figure 18 - Decay of the initial concentration of MBAS (61.6, 34.8 and 22.7 mg L^{-1}) as a function of time, during 315 min of treatment applying 10.0 V at initial pH 5.5 and the respective percentage of MBAS reduction in comparison with the limit of Resolution 181/21 of Consema/SC (2.0 mg L^{-1})



The Figure 19, which represents the derivative of the MBAS concentration as a function of time for the study of the different concentrations evaluated, illustrates the rate of reduction of MBAS over time for each initial MBAS concentration condition at pH 5.5, with application of an electrical potential of 10.0 V

Figure 19 – Derivative of MBAS concentration as a function of time, for initial concentrations of 61.6, 34.8 and 22.7 mg L^{-1} of MBAS during 315 min of treatment applying 10.0 V at an initial pH of 5.5



From the illustration in Figure 19, it can be seen that the reduction rate is high in the first 90 min of treatment and begins to reduce from that time onwards. This proves that the reduction of MBAS by EC, under the experimental conditions used, is dependent on the process time, regardless of the initial concentration range presented.

3.8 Laboratory analysis of the composition of raw and post-treated VWSE

The chemical characterization of raw VWSE and VWSE after EC treatment in potentiostatic mode with an electric potential of 10.0 V, using Al electrodes, for an EC process time of 330 min, applying 10.0 V at pH 5.5, is presented in Table 4. The EC process time evaluated in this case was increased to 330 min precisely to have a value slightly above the limit evaluated throughout the kinetic study and to ensure greater safety in the evaluation. For this purpose, a new sample was collected at a vehicle wash station. The table presents values of concentration of metals and non-metals, concentration of OGs, COD, MBAS, turbidity, total coliforms and thermotolerant coliforms, obtained in a certified laboratory.

Table 4- Concentration of constituents in raw VWSE and post-treated by EC applying an electric potential of 10.0 V at an initial pH of 5.5 for 330 min

Paramter	Raw effluent	Treated effluent	% of reduction
OG (mg L^{-1})	NA	<10	-
DQO (mgo_2 L^{-1})	609	62.4	89.75
MBAS (mg L^{-1})	66.3	0.78	98.82
Al (mg L^{-1})	12.97	19.0	-46.51
Ba (mg L^{-1})	0.392	<0.01	>99.99
Cd (mg L^{-1})	0.003	<0.001	>99.99
Ca (mg L^{-1})	9.87	0.72	92.66
Pb (mg L^{-1})	0.039	<0.01	>99.99
Co (mg L^{-1})	0.014	<0.01	>99.99
Cu (mg L^{-1})	0.572	0.011	98.08
Cr (mg L^{-1})	0.024	<0.01	>99.99
Sn (mg L^{-1})	0.013	<0.01	>99.99
Fe (mg L^{-1})	11.03	0.043	99.61
P (mg L^{-1})	0.566	0.017	97.0
Li (mg L^{-1})	0.065	0.018	72.30
Mg (mg L^{-1})	2.961	0.168	94.30
Mn (mg L^{-1})	0.689	<0.01	>99.99
Ni (mg L^{-1})	0.026	<0.01	>99.99
Ti (mg L^{-1})	0.171	<0.01	>99.99
Si (mg L^{-1})	28.65	0.031	99.89
Na (mg L^{-1})	95.85	324.42	-338.40
Vn (mg L^{-1})	0.031	0.014	45.16
Zn (mg L^{-1})	1.030	<0.01	>99.99

*NA = Not evaluated

Regarding the MBAS concentration, whose limit established by resolution 181/2021 of CONSEMA/SC is 2.0 mg L^{-1}, the VWSE after treatment met the established standard. Likewise, the COD concentration, regulated by resolution 182/2021 of the same agency, was below the limit of 210.0 mg_{O2} L^{-1}, as well as the total OGs content, which are limited to 60 mg L^{-1} by resolution 182/2021 of the same agency. Regarding the OGs concentration, whose limit established by resolution 182/2021 of CONSEMA/SC is 60.0 mg L^{-1}, the raw VWSE was within the limit, even before EC treatment. Likewise, the COD concentration after the EC process was 62.4 mg_{O2} L^{-1}, regulated by resolution 182/2021 of the same agency, was below the limit of 210.0 mg_{O2} L^{-1}, as well as the MBAS concentration whose limit established by resolution 181/2021 of CONSEMA/SC is 2.0 mg L^{-1} and was reduced from 66.3 mg L^{-1} to 0.78 mg L^{-1} after 330 min of EC process. The results of this table also point to the reduction of parameters with efficiencies greater than 45% for Vanadium (Vn) and between 70.0%-100% for the other metals.

Observing CONAMA resolution 430/2011, which establishes the standards for effluent discharge in Brazil, it was found that, with the exception of Bo, F^-, Hg, Ag, Se and NH_3, which are not covered by this resolution, establishes limit values such as Ba, 5.0 mg L^{-1}, Cd 0.2 mg L^{-1}, Pb 0.5 mg L^{-1}, Fe 15.0 mg L^{-1}, Cu 1.0 mg L^{-1}, Mn 1.0 mg L^{-1}, Ni 2.0 mg L^{-1}, Zn 5.0 mg L^{-1}, Sn 4.0 mg L^{-1}. It was demonstrated that after the EC

process under the adopted conditions, these parameters meet the release according to this resolution.

Regarding the metal content in raw VWSE, Rai et al. (2019) during the analysis of the impacts of vehicle wash wastewater on aquatic organisms, analyzed 6 different discharge points of two rivers in cities located in Bhutan (Asia). The authors determined concentrations of some metals such as Fe (0.5-2.0 mg L^{-1}), Mn (0.03-0.04 mg L^{-1}), Zn (0.01-0.06 mg L^{-1}) and Pb (0.02-0.04 mg L^{-1}) and also pointed out in the research that the variables, COD, pH, TSS, turbidity and OGs, significantly deteriorate the ecological state of equilibrium and the aquatic benthic macro-invertebrate organisms.

The presence of Fe in car wash effluent was noted by Torrens et al. (2026), with concentrations ranging from 0.6 to 8.5 mg L^{-1} for Fe, 0.33 to 0.73 mg L^{-1} for Zn, and 1.0 to 3.0 mg L^{-1} for MBAS. Xiang et al. (2024) reported COD and P values of 422.0 mgo_2 L^{-1} and 6.7 mg L^{-1}, respectively, in raw effluent, and 50.0 mgo_2 L^{-1} and 0.8 mg L^{-1} in treated effluent using a Sequencing Batch Reactor (SBR). Regarding the presence of metals in raw VWSE, varying concentrations were detected and many of these metals, such as (Al, Cr, Fe, Mn and Zn) were also found in previous studies, such as that of Zini et al. (2020), in effluent from the automotive industry, other metals such as (Na, Ca, K, Zn, Fe, Pb, Cd and Cr) in the study by Gomes et al. (2016), in truck wash effluent and (Cu, Co, Zn, Ni and Pb) in the study by Nguegang, Sibanda and Tekere (2020).

However, Al and sodium (Na), after treatment by EC presented higher values when compared to raw VWSE. This is due to the oxidized electrode and the electrical conductivity adjustment solution (NaCl solution) in solution. However, there is no specific indication for Al in the limits indicated for the release of effluents. In the state of SC, there is no indication of the limit concentration of Al in effluents and in the state of RS, the local regulatory body stipulates the limit of 10.0 mg L^{-1} for this metal in effluents discharged into receiving bodies. For Fe, CONAMA Resolution 430/2011 indicates the limit of 15.0 mg L^{-1} for the discharge of effluents; therefore, the final value determined in the VWSE in this study meets this standard.

For the parameters presented in Table 4, the EC process under the conditions used was effective in reducing them, as shown. The values for the chemical elements Al and Na, whose reduction percentages were negative, represent the fact that Na is added to the support electrolyte solution to increase the electrical conductivity of the solution (approximately 227.0 mg L^{-1} of sodium) as NaCl and Al correspond to electrode material that was oxidized in the process. Furthermore, with regard to sodium, the sum of the added value of support electrolyte with the value presented in the composition of the raw VWSE represents the value measured in the treated VWSE. It is also worth mentioning that the raw VWSE had 12.0 mg L^{-1} of Al and after treatment, the measured value represented an increase of another 7.0 mg L^{-1} of this metal in solution.

Conclusion

The effect of time, pH, electric potential and electric current density on the reduction of COD, MBAS and turbidity was investigated. The results showed that the potentiostatic mode presented better operational conditions for reducing the parameters. Furthermore, the pH and treatment time evaluated demonstrated that they influence the process of reducing the parameters. The pH of 5.5 and the EC time of 315 min allowed the greatest efficiency in reducing MBAS, which was shown to be the contaminant with the slowest reduction kinetics, requiring a longer EC time than the COD and turbidity parameters monitored throughout the study. In addition, it was possible to reduce a wide range of metals and non-metals present in VWSE that can contribute to pollution or alter the characteristics of water bodies.

The kinetic study with the 1.6 L reactor demonstrated that EC with Al electrodes can be applied for the treatment of VWSE. In addition, it was shown that treatment time and pH are important parameters in the process. Using an electrical potential of 10.0 V and pH 5.5, it was possible to reduce turbidity by up to 95%, and COD and MBAS by up to 98% using the EC process for 315 min, which was the time interval used for all parameters at the end, due to the kinetics of MBAS.

The analysis of a new batch of samples collected and treated in the reactor under the best determined conditions (pH 5.5; DE = 2.0 cm, electrical potential of 10.0 V for 330 min) was presented and through it, significant reductions in the COD and MBAS parameters were determined, being 89.8% for COD and 98.8% for MBAS. The values comply with legislation 181/2021 and 182/2021 of Consema/SC. With the data obtained, there are good indications that it is possible to carry out new EC studies applied to the treatment of VWSE and propose the mathematical modeling of a reactor for the treatment of VWSE to reduce contaminants, based on the use of the parameters studied and results presented here.

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