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Application of electroc hemical processes in aerobic biological systems used for textile wastewater treatment: effects on mixed liquor characteristics and pollutant removal

Aplicação de processos eletroquímicos em sistemas biológicos aeróbios empregados no tratamento de efluentes têxteis: efeitos nas características do licor misto e na remoção de poluentes

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ABSTRACT

This study evaluated the influence of electrochemical process application on pollutant removal and changes in the characteristics of mixed liquor in aerobic biological systems used for textile wastewater treatment. For this purpose, samples of mixed liquor containing synthetic textile wastewater (nitrogen, phosphorus, acetate, and Drimaren Red CL-7B dye) were introduced into bench-scale reactors operated under two experimental conditions: in the first condition, the application was performed with a current density of 20 A m^{-2}, using an intermittent exposure mode of 6 min on / 30 min off (Strategy 1 – S1), while in the second, the same current density was applied but under continuous exposure (Strategy 2 – S2). A control reactor was operated simultaneously for comparison purposes, evaluating pollutant removal and the filterability of the mixed liquor. The results indicated that electrochemical processes improved the filterability of the mixed liquor by 35% in S1 and 44% in S2. Dye removal ranged from 40 to 50% in the control reactor, reaching 67% in S1 and 93% in S2 with the application of electric current. Regarding phosphorus, the application of electric current increased removal from 30% in the control reactor to 67% in S1 and 96% in S2. No significant changes were identified in the content of total suspended solids with intermittent application. However, under continuous exposure, an increase of approximately 30% was observed. It was concluded that the application of electrochemical processes can be a promising alternative to enhance the performance and stability of biological treatment systems applied to textile wastewater treatment.

Keywords: textile industry; membrane bioreactors; electrocoagulation; advanced treatment.

RESUMO

Avaliou-se no presente estudo a influência da aplicação de processos eletroquímicos na remoção de poluentes e na alteração das características do licor misto de sistemas biológicos aeróbios empregados no tratamento de efluentes têxteis. Para tanto, amostras de licor misto contendo efluente têxtil sintético (nitrogênio, fósforo, acetato e corante Drimaren Red CL-7B) foram inseridas em reatores de bancada operados sob duas condições experimentais: na primeira, a aplicação foi realizada com densidade de corrente de 20 A m^{-2}, com modo de exposição intermitente de 6 min ligado / 30 min desligado (Estratégia 1 - E1); enquanto na segunda, utilizou-se a mesma densidade de corrente, porém, com exposição contínua (Estratégia 2 - E2). Um reator controle foi operado simultaneamente para fins de comparação, avaliando a remoção de poluentes e a filtrabilidade do licor misto. Os resultados indicaram que os processos eletroquímicos melhoraram a filtrabilidade do licor misto em 35% na E1 e 44% na E2. A remoção de corante variou de 40 a 50% no reator controle, alcançando 67% na E1 e 93% na E2, com aplicação de corrente elétrica. Em relação ao fósforo, a aplicação de corrente elétrica elevou a remoção de 30% no reator controle para 67% na E1 e 96% na E2. Não foram identificadas alterações significativas no teor de sólidos suspensos totais com a aplicação intermitente. No entanto, sob exposição contínua, observou-se um aumento de aproximadamente 30%. Concluiu-se que a aplicação de processos eletroquímicos pode ser uma alternativa promissora para melhorar o desempenho e a estabilidade dos sistemas de tratamento biológico aplicados ao tratamento de efluentes têxteis.

Palavras-chave: indústria têxtil; biorreatores a membrana; eletrocoagulação; tratamento avançado.

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Introduction

The growing global demand for clothing and textiles has driven the expansion of the textile industry, making it a key sector in the global economy and a major source of employment and income. Brazil is one of the four largest knitwear producers in the world and has the largest fully integrated textile chain in the Western world (Abit, 2023).

Textile production is water-intensive, resulting in large volumes of wastewater (Wang et al., 2022). Wastewater from the dyeing phase is particularly problematic due to the presence of azo dyes, which despite being highly soluble, low-cost, and widely used, are also toxic and recalcitrant (Silva and Fracacio, 2021). In addition to dyes, textile wastewater also contains other potentially harmful components, such as organic matter, salts, nutrients, phenols, and surfactants, which can contribute to water pollution and cause various adverse effects, including visual pollution, disruptions in biological cycles, and harm to natural processes like photosynthesis (Wang et al., 2022).

As a result, various national and international regulations have been developed to mitigate the environmental impacts of industrial wastewater, including those of the textile industry. In Brazil, the National Environment Council (CONAMA, *Conselho Nacional do Meio Ambiente*) Resolution No. 430/2011 (Brasil, 2011) stands out, which outlines the conditions and standards for wastewater discharge into water bodies, setting maximum concentration limits for various organic and inorganic pollutants. According to this regulation, treated wastewater must meet quality standards before being discharged into water bodies, aiming to protect aquatic ecosystems and human health.

Textile wastewater treatment generally combines conventional physical, chemical, and biological processes, which are not always effective for dye removal (Silva and Fracacio, 2021; Otto et al., 2021). Additionally, the partial degradation of dyes can generate toxic by-products, such as aromatic amines, which are harmful to aquatic organisms (Albahnasawi et al., 2020). With increasing environmental requirements, there is a growing demand for more efficient technologies, prioritizing reuse whenever possible (Soler and Xavier, 2015; Quadrelli Neto et al., 2018). In Brazil, The National Council of Water Resources (CNRH, *Conselho Nacional de Recursos Hídricos*) Resolution No. 54/2005 (Brasil, 2005) encourages the reuse of treated wastewater, with an emphasis on regions subject to water scarcity, aiming to reduce water consumption and mitigate environmental impacts in industry, thereby reinforcing the relevance of advanced treatment technologies. However, there is still no specific national regulation that sets technical requirements for wastewater reuse in industrial applications. Considering this gap, international standards, such as the United States Environmental Protection Agency guidelines, can be used as references, providing detailed standards for different reuse scenarios (EPA, 2012).

In this regard, membrane bioreactors (MBRs) emerge as a promising alternative for textile wastewater treatment, producing high-quality effluents (Jegatheesan et al., 2016). MBRs have characteristics similar to conventional activated sludge processes; however, the sedimentation stage is replaced by membrane filtration. It is worth noting that, although conventional systems have lower initial installation costs, MBRs stand out in the long term due to their ability to produce high-quality effluents and reduce the area required for installation. Additionally, the lower sludge generation in MBRs contributes to the reduction of final disposal costs, a significant component in the overall budget of wastewater treatment plants (Park et al., 2015; Giwa et al., 2019).

Despite the reported advantages, membrane fouling is still considered one of the main challenges in the use of these systems, as it directly affects their performance, increasing the cleaning frequency and aeration requirements, as well as reducing membrane productivity and lifespan (Park et al., 2015). According to Du et al. (2020), fouling is defined as the accumulation of substances inside the pores of a membrane or on its surface, causing an increase in transmembrane pressure under constant flow conditions or a loss in permeate flow under constant pressure conditions.

As an alternative to fouling control, Asif et al. (2020) suggest the use of electrochemical processes in conjunction with MBRs. For this purpose, metallic electrodes are inserted into the reactor, and a low-intensity electric current is applied, inducing the release of ions and promoting the occurrence of electrocoagulation, electroosmosis, and electrophoresis processes (Mollah et al., 2004). This strategy allows for the maximization of phosphorus, organic matter, and textile dye removal capacity, and, most importantly, provides greater operational stability to the system by reducing soluble and colloidal compounds in the mixed liquor, resulting in minimized fouling (Belli et al., 2019; Giwa et al., 2019; Ravadelli et al., 2021).

However, it is important to emphasize that, as this is a recent technology, the relevant literature still lacks detailed information on the recommended operational conditions for applying low-intensity electric currents in conjunction with biological processes, especially for industrial wastewater treatment. In this context, the present study aimed to evaluate the influence of electrochemical processes on the dye and nutrient removal capacity, as well as on the alteration of the physicochemical characteristics of the mixed liquor in aerobic biological systems, simulating the conditions typically observed in MBRs applied to textile wastewater treatment.

Material and Methods

The experiments were carried out in an experimental unit consisting of two bench-scale reactors (Figure 1), with configurations defined based on the previous study by Battistelli et al. (2019a). Each reactor had a usable volume of 1.0 L and was equipped with metallic electrodes measuring 5.5 x 14.0 cm, spaced 5.0 cm apart, to allow the application of electric current. The anode was made of a flat aluminum plate, while the cathode consisted of a stainless- steel plate, both perforated with approximately 46% of the surface area.

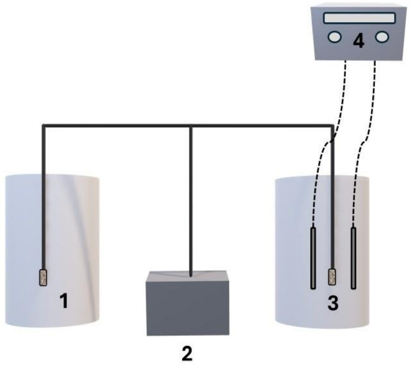

Figure 1 – Schematic representation of the bench-scale reactors used in this study. 1) Conventional reactor; 2) Air compressor; 3) Reactor with applied electric current; 4) DC power supply.

In the first reactor, operated as a control, there was no connection to the electrical system, allowing operation without the application of current for comparison purposes. The second reactor was operated in parallel, with the current density controlled by a digitally adjustable DC power supply (PS A305D), with a voltage range of 0–30 V and a current range of 0–5 A. The exposure mode was regulated by a digital timer, installed between the power supply and the electrodes. The provision of oxygen to the microorganisms, as well as the maintenance of the complete mixing regime in the reactors, was achieved using air diffusers connected to an air blower with two outlets and a flow rate of 4.0 L min^{-1} (Boyu/S-2000A).

Experimental procedure

To initiate the operation, the reactors were inoculated with mixed liquor obtained from the aeration tank of an industrial wastewater treatment plant utilizing activated sludge technology. Due to the low solids content of the collected sludge (approximately 400 mg L^{-1}), an initial concentration step was performed to simulate characteristics typically used for treating textile wastewater in aerobic MBRs (1000–15000 mg L^{-1}) and to standardize the conditions across different experiments (Jegatheesan et al., 2016). To achieve this, the sludge underwent sedimentation for 2 hours. Subsequently, the supernatant was removed, and 700 mL of concentrated sludge (approximately 3000 mg L^{-1}) was added to each reactor.

Next, 100 mL of concentrated synthetic textile wastewater was added to the reactors. This wastewater was produced using azo dye (Drimaren Red CL-7B), following the procedure described by Spagni et al. (2010), and its composition is illustrated in Table 1.

After the inoculum was introduced and the synthetic wastewater was added to the reactors, the experiments were conducted over 24 hours, with the ambient temperature controlled at 23°C. The objective was to evaluate the removal of dye and the modification of the mixed liquor characteristics. During this period, two experimental conditions were tested in triplicate. In the first condition, an electric current density of 20 A m^2 was applied with intermittent exposure mode (6 minutes on / 30 minutes off) (Strategy 1 – S1). In the second, the same current density (20 A m^{-2}) was used but under continuous exposure (Strategy 2 – S2). The experimental conditions were defined based on results previously obtained by Belli et al. (2019) and Ravadelli et al. (2021). In both strategies, a separate reactor was operated under the same operational conditions but without the application of electrical current, for comparison purposes.

Evaluation of pollutant removal efficiency

In order to evaluate the efficiency of the electrochemical processes in the removal of pollutants, the samples were characterized before and after treatment, both in the system subjected to electrical current application and in the conventional system (control), for the following parameters: dye concentration, true color, soluble phosphate ($P\text{-}PO_4^{-3}$) and ammoniacal nitrogen ($N\text{-}NH_4^+$). For this, the samples were pre-filtered using a filtration setup equipped with a cellulose acetate membrane with an average pore size of 0.45 µm. The readings were performed using an ultraviolet visible (UV-Vis) HACH 6000 absorption spectrophotometer.

To determine the dye concentration and its respective removal, a spectral scan of the raw wastewater was first performed between 380 and 740 nm to identify the absorption peak corresponding to the dye (517 nm). Then, an analytical curve was introduced into the equipment using different dye concentrations (between 10 and 50 mg L^{-1}), which enabled the measurements to be carried out. Additionally, at the end of each experimental strategy, absorbance readings were also taken between 200 and 800 nm. This analysis aimed to visualize the changes in absorbance across the UV-Vis spectrum and identify possible compounds formed as a result of the dye molecule degradation.

Table 1 – Composition of synthetic wastewater and initial operating concentrations in the reactors.

Compound	Chemical formula	Concentration in synthetic wastewater	Concentration in reactors
Ammonium chloride	NH_4Cl	320.0 mgN L^{-1}	40.0 mgN L^{-1}
Dipotassium phosphate	K_2HPO_4	35.6 mgP L^{-1}	4.45 mgP L^{-1}
Monopotassium phosphate	KH_2PO_4	36.4 mgP L^{-1}	4.55 mgP L^{-1}
Azo dye (Drimaren Red CL-7B)	---	400.0 mg L^{-1}	50.0 mg L^{-1}
Sodium acetate	$C_2H_3NaO_2$	8000 mgCOD L^{-1}	1000 mgCOD L^{-1}

Source: adapted from Spagni et al. (2010).

The determination of true color ($N\text{-}NH_4^+$ and $P\text{-}PO_4^{-3}$) was performed following the methods described in the Standard Methods for the Examination of Water and Wastewater (APHA, 2005). For true color, the spectrophotometric method 2120 C was used. For $N\text{-}NH_4^+$ analysis, the Indotest Ammonia Spectro Kit (Alfakit) was used, employing the Phenate method – 4500-NH_3. For $P\text{-}PO_4^{-3}$ quantification, the Ascorbic Acid method – 4500-P E was used.

Evaluation of mixed liquor characteristics

To evaluate the characteristics of the mixed liquor, the following analyses were performed before and after the application of electric current: solids content, diluted sludge volume index (DSVI), modified fouling index (MFI), conductivity, and potential hydrogen (pH). The methodologies used for these analyses are described below.

To determine the mixed liquor solids content, the fractions of total suspended solids (TSS), volatile suspended solids (VSS), and fixed suspended solids (FSS) were quantified. The gravimetric method described in the Standard Methods for the Examination of Water and Wastewater was employed for this analysis (APHA, 2005).

The sludge volume index (SVI) is a commonly used parameter to measure sludge settleability but it can also be related to the filterability of mixed liquor in MBRs (Sun et al., 2007). Due to the high concentration of solids in the mixed liquor, the test to determine the SVI was conducted using diluted mixed liquor, hence referred to as DSVI. This procedure was carried out to ensure that the volume of settled sludge after 30 minutes was below 200 mL, following the protocol described by Jenkins et al. (2003). After the sedimentation period, a sample of the supernatant was also collected to determine the residual turbidity by the nephelometric method, using a bench turbidity meter (Del Lab, model DLI-2500).

The MFI determination test was conducted in a bench-scale filtration unit, equipped with a cellulose acetate membrane with a pore size of 0.45 µm. For this test, a 250 mL sample of mixed liquor was pressurized at a constant pressure of 0.167 bar, using a synthetic air cylinder, for over 20 minutes. The permeate was collected in a beaker placed on an analytical balance, allowing the mass accumulated every 30 seconds to be recorded. This enabled the conversion into volume, which is necessary for calculating the filtration flux. A time/filtrate volume (t/V) versus permeate volume (V) graph was plotted for each sample. The MFI was obtained through the slope of the line, in $s\ mL^{-1}$ (Schippers and Verdouw, 1980).

The pH of the mixed liquor was determined by direct reading with a PG1800 bench pH meter, brand Gehaka. The equipment was pre-calibrated, and the measurement was then performed following the manufacturer's instructions.

Results and Discussion

Evaluation of the solid contents and pH

Table 2 presents the results obtained for the contents of TSS, VSS, and FSS, as well as the calculated values for the VSS/TSS ratio in both experimental strategies, before and after the application of electric current.

There is little variation in the levels of TSS, VSS, and FSS during S1, both under conditions with and without the application of electric current. This scenario suggests that the operational conditions employed in this strategy did not cause significant changes in the characteristics of the mixed liquor. Furthermore, the stability of the FSS values also indicates that no significant accumulation of aluminum occurred in the mixed liquor, which could negatively affect the biomass activity due to its toxicity and complicate the management of the generated sludge (Asif et al., 2020).

In S2, on the other hand, the initial values of VSS and TSS were slightly higher than S1, which may be attributed to the variation in the characteristics of the inoculum. Despite this, it is important to note that a considerable increase in the TSS levels was identified after the application of electric current. This increase was predominantly attributed to FSS content growth, as the variation in the VSS values was not as significant. Hasan et al. (2014) also identified an increase in the fixed solids content in the mixed liquor in a domestic wastewater treatment system using electrochemical processes with sacrificial electrodes. According to these authors, the increase in FSS content occurs due to the accumulation of complexes formed by colloidal particles and soluble organic pollutants with Al^{3+} ions released into the mixed liquor from the electric current application.

It is also important to emphasize that the VSS/TSS ratio observed in all conditions was below the recommended value of 0.85 for the operation of biological reactors (Metcalf and Eddy, 2014). In S2, this value was even lower, suggesting a negative influence of the electrochemical process. However, it is worth noting that this is an expected behavior, since in biological treatment systems combined with the application of electric currents, especially in continuous mode, the oxidation of the metal anode and the formation of inorganic compounds in the mixed liquor typically result in a VSS/TSS ratio between 0.5 and 0.7 (Hua et al., 2015; Battistelli et al., 2019b; Belli et al., 2023).

Table 2 – Average values of total suspended solids, volatile suspended solids, fixed suspended solids, and the volatile suspended solids/total suspended solids ratio for Strategies 1 and 2.

Strategy	Experimental Condition	TSS ($mg\ L^{-1}$)	VSS ($mg\ L^{-1}$)	FSS ($mg\ L^{-1}$)	VSS/TSS ratio
S1	No current application	2703±264	2080±300	623±49	0.77
	Intermittent current application	2637±245	2020±238	617±51	0.77
S2	No current application	32 67±383	2440±248	827±137	0.75
	Continuous current application	4203±739	2383±592	1820±147	0.57

TSS: total suspended solids; VSS: volatile suspended solids; FSS: fixed suspended solids; ±: standard deviation.

The pH values of the mixed liquor, in turn, showed little variation during S1, with average values of 8.21 standard deviation (±) 0.07 and 8.31±0.34 in the conditions without and with the application of electric current, respectively. In S2, the observed average values were 7.67±0.32 in the conventional condition and 8.52±0.40 with the application of the electric current. Harif et al. (2012) mentioned that during the electrocoagulation process, the generation of aluminum hydroxides uses the hydroxyl ions formed, but not all of the produced amount is utilized. Therefore, the hydroxyl ions generated may accumulate in the solution, increasing pH.

As reported by Khan et al. (2013), the pH of the mixed liquor plays a significant role in the treatment of textile wastewater in biological systems, with the recommended optimal range varying between 6.0 and 10.0. Furthermore, Shahedi et al. (2020) related that the chemical dissolution of aluminum is highly influenced by pH, as the dissolution rate of the electrode is directly proportional to the pH of the medium. Under these conditions, metal hydroxides are also produced, which enhances the contaminant removal capacity. Therefore, more basic pH values may contribute to the increased efficiency of the electrocoagulation mechanism.

These findings indicate that the application of electric current plays a significant role in the composition of solids in mixed liquor, directly impacting the characteristics that influence the efficiency of biological reactors. Understanding these changes is crucial for improving treatment performance and developing strategies that promote synergy between electrochemical and biological processes in a single reactor.

Evaluation of textile dye removal and true color

The average values for textile dye concentration and true color, along with the removal efficiencies observed in both experimental strategies, before and after the application of electrochemical processes, are presented in Table 3. It is possible to observe that the removal of dye and true color was proportional and occurred in all the evaluated conditions. These results indicate that, even in conditions where the electric current was not applied, the system could promote partial removal of the dye, with efficiencies ranging from 40 to 51%, and true color, from 30 to 41%.

According to Albahnasawi et al. (2020), the microbiological degradation of this type of dye generally requires anaerobic conditions, as the cleavage of the azo bond, essential for decolorization, primarily occurs in reducing environments. Thus, it is believed that the observed removal can be mainly attributed to the adsorption of the dye on the surface of the biological flocs (Khan et al., 2013). In this context, the higher dye removal efficiency identified in S2 compared to S1 can be attributed to the higher TSS content identified in this strategy, as evidenced in the previous section, which may have contributed to greater removal capacity due to the increased adsorption surface area in the mixed liquor flocs.

From the results obtained, it is also possible to confirm that the application of electric current in the mixed liquor led to an increase in dye removal efficiency in both strategies. In S1, where the electric current was applied intermittently, the removal efficiency increased from 40 to 67%. In the condition with continuous current application (S2), the increase was even more significant, rising from 51 to 93%, resulting in a treated effluent with a dye concentration close to 3.0 mg L^{-1}. This can be attributed to the fact that aluminum released by the electrode can react with dye, promoting its precipitation and subsequent removal (Sahu et al., 2014; Ravadelli et al., 2021). Besides that, electrochemical oxidation may have also contributed to this increase in efficiency, as the application of electric current in the mixed liquor can also generate oxidants, which enhance the biodegradability of complex compounds, such as dyes (Hua et al., 2015; Giwa et al., 2019).

This phenomenon also explains the higher efficiencies of dye and true color removal achieved in S2 compared to S1, since the electric current was applied continuously in the second strategy, resulting in the release of more aluminum ions that can react with the dye. These results indicate that the application of electrochemical processes can contribute to the removal of textile dyes from wastewater, acting as a com-

Table 3 – Average values of textile dye concentration and true color, and the respective removal efficiencies obtained for Strategies 1 and 2.

Strategy	Experimental Condition (%)	Dye (mg L^{-1})	True Color (uC)
S1	Raw wastewater	49.13±2.78	1302±50
	No current application *Removal*	29.72±1.14 *40*	912±120 *30*
	Intermittent current application	16.18±2.89	512±128
	Removal	*67*	*61*
S2	Raw wastewater	46.21±2.23	1236±31
	No current application *Removal*	22.84±5.08 *51*	728±163 *41*
	Continuous current application	3.01±1.14	122±41
	Removal	*93*	*90*

plementary process to microbiological degradation and adsorption on the surface of the flocs. Belli et al. (2023) evaluated the removal of azo textile dye in an anoxic/aerobic membrane electro-bioreactor, employing two operational conditions in terms of exposure to electric current (6 min on / 30 min off and 6 min on / 12 min off). The authors revealed that both tested conditions allowed for high dye removal efficiency (greater than 94%); however, they suggested that the condition with better cost-effectiveness was the 6 min on / 30 min off mode, as the energy demand was almost twice lower.

In this context, to better understand the mechanisms involved in the dye removal observed in the present study, spectrophotometric monitoring was performed on the wastewater before and after treatment, as this analysis is capable of showing the absorbance obtained at different wavelengths of the UV-Vis spectrum (Figure 2).

Based on the results obtained from the absorbance analysis in the UV-Vis region, a reduction in the spectral area is observed in both strategies, even under conditions without the occurrence of electrochemical processes. During S1, the reduction in the spectral area was 74.1% in the experimental condition without the application of electric current and 81.2% with intermittent electric current application. In S2, this reduction was even more significant, reaching 75.5% in the conventional condition and 87.8% with continuous electric current application.

It is also noted that at the wavelength of 517 nm, corresponding to the absorption peak of the Drimaren Red CL-7B dye, the reduction in absorbance was even more intense, especially under conditions with continuous electric current application (S2), indicating an effective contribution of electrochemical processes and corroborating the results obtained for true color and dye removal presented earlier.

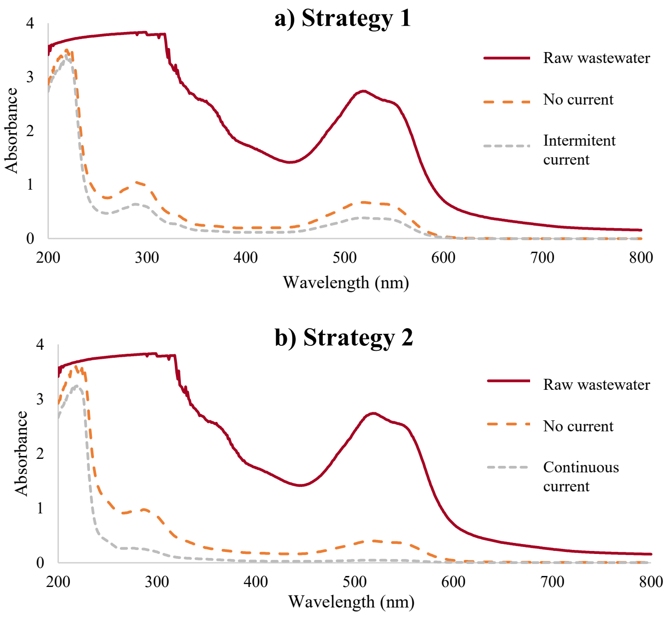

Figure 2 – Ultraviolet visible absorbance of the synthetic wastewater before and after treatment for Strategy 1 (a) and Strategy 2 (b).

Similar results were observed by Belli et al. (2019) during the operation of an electro-membrane bioreactor (e-MBR) for textile wastewater treatment. The authors related that the enhancement in dye removal during the strategies with electric current application can be attributed to the electrochemical processes occurring in the reactor, particularly to the interaction of dye molecules with aluminum released into the mixed liquor, leading to the formation of insoluble compounds that are easily retained in the filtration process by the membrane.

On the other hand, it is also possible to observe absorbance peaks at a wavelength close to 280 nm, identified as the maximum absorption point for aromatic amines (Belli et al., 2024). Albahnasawi et al. (2020) reported that aromatic amines can be even more harmful to the environment than the dye itself due to their toxic and carcinogenic characteristics, indicating the importance of their proper removal before discharge into water bodies or reuse.

In this context, it is important to highlight that a significant reduction of this peak (280 nm) was noted under the conditions where electric current was applied, especially continuously. Therefore, it is believed that the occurrence of electrochemical processes, such as electrocoagulation and electrochemical oxidation, may have contributed to the removal of aromatic amines. Belli et al. (2024), in a study involving the treatment of wastewater containing azo dye in an anaerobic reactor combined with an e-MBR, also observed similar results. These authors stated that the absorbance of permeate samples in the ultraviolet range was lower when the system was operated with electric current application, which contributed to the reduction of the effluent's toxic potential.

Additionally, elevated absorbance values can also be seen in the range between 200 and 250 nm across all the tested conditions. According to Guo et al. (2020), these peaks could be related to the presence of nitrite and nitrate, indicating the likely occurrence of the nitrification process. However, it is noteworthy that these peaks were reduced under conditions with electric current application, which may be related to the occurrence of negative effects on the activity of nitrifying microorganisms (Sorgato et al., 2023).

Evaluation of nutrient removal

Table 4 shows the average values obtained for the concentrations of phosphorus and ammoniacal nitrogen, as well as the respective removal efficiencies observed in both experimental strategies, with and without the application of electric current.

According to Metcalf and Eddy (2014), phosphorus removal via cellular synthesis is quite limited in biological effluent treatment systems, contributing to about 10 to 30% of the overall process efficiency. In the present study, it is believed that this mechanism can explain the observed phosphorus removal even under conditions without the application of electric current and, consequently, the absence of the electrocoagulation process. On the other hand, under

Table 4 – Average values of phosphate ($P\text{-}PO_4^{-3}$) and ammoniacal nitrogen ($N\text{-}NH_4^+$) concentrations, along with the respective removal efficiencies achieved.

Strategy	Experimental Condition	$P\text{-}PO_4^{-3}$ (mg L^{-1})	$N\text{-}NH_4^+$ (mg L^{-1})
S1	Raw wastewater	4.92±0.15	41.89±2.13
	No current application	3.54±0.43	8.93±4.21
	Removal (%)	*28*	*79*
	Intermittent current application	1.64±0.60	12.83±4.07
	Removal (%)	*67*	*69*
S2	Raw wastewater	4.99±0.20	36.34±1.75
	No current application	3.57±0.28	3.43±2.36
	Removal (%)	*28*	*91*
	Continuous current application	0.18±0.08	9.83±7.09
	Removal (%)	*96*	*73*

conditions with electrocoagulation, the aluminum released from the electrode can react with the soluble phosphate present in the effluent, allowing its precipitation and subsequent removal (Mollah et al., 2004). Therefore, this reaction is assumed to be responsible for the significant increase in phosphorus removal observed under operational conditions where electrochemical processes occurred, achieving 96% removal efficiency when the electric current was applied continuously.

Similar results were observed by Hasan et al. (2014), who employed an electrocoagulation system combined with membrane filtration for treating domestic wastewater. They achieved an average 99.9% removal of $P\text{-}PO_4^{3-}$ using a current density of 12 A m^{-2}. Based on the authors, in addition to the electrocoagulation and precipitation mechanisms, inorganic phosphorus fractions can also be deposited on the cathode surface, contributing to the overall phosphorus removal efficiency. Yan et al. (2012), on the other hand, investigated the effects of applying polyaluminum chloride (40 mg L^{-1}) in an MBR for textile wastewater treatment. Their results showed an increase in phosphorus removal from about 28% under conventional conditions to 98.0% after coagulant application, indicating that electrocoagulation can achieve efficiencies similar to those of conventional coagulation processes.

Regarding $N\text{-}NH_4^+$, its removal in biological processes can occur in two main ways: through nitrification or assimilation by bacteria, which use it in cellular synthesis for microbial growth, similar to phosphorus. However, it should be noted that assimilation is relatively low, typically accounting for no more than 30% of the total nitrogen in effluents treated by biological systems (Metcalf and Eddy, 2014). In this case, it is believed that the removal observed in the present study, exceeding 69% in all tested conditions, likely occurred through both cellular synthesis and the nitrification process, facilitated by the favorable environmental conditions, such as pH and dissolved oxygen concentration (>5.0 mg L^{-1}).

However, it is important to highlight that, in both strategies, the ammoniacal nitrogen removal efficiency was lower under conditions where the electrical current was applied, compared to conventional conditions, which aligns with the findings from the UV-Vis absorbance analysis. According to Asif et al. (2020), the application of electrical currents in biological systems is a complex process due to the potential adverse effects that electricity can have on microbial activity, including nitrifying bacteria. Furthermore, Sorgato et al. (2023) indicated that the activity of these microorganisms is significantly affected by the presence of aluminum in the mixed liquor, with negative effects being directly proportional to its concentration, which may explain the lower removal efficiency observed under conditions with electrochemical processes. Tong et al. (2019) suggested that it is crucial to find an optimal current density to avoid harming nitrification, as very high current densities can negatively affect ammoniacal nitrogen removal. Nonetheless, it should be noted that the ammoniacal nitrogen concentrations identified in all conditions met the standards established by Brazilian legislation for discharge into water bodies (20 mg L^{-1}) (Brasil, 2011), while also enhancing its potential for reuse.

Evaluation of mixed liquor filterability and settleability

Table 5 presents the observed results for MFI, DSVI, and turbidity levels in both experimental strategies, with and without the application of electric current.

Based on the results obtained, it can be observed that in S1, the MFI was about 35% lower in the condition with electric current application than in the conventional configuration. In S2, the MFI with electric current application was 44% lower than in the conventional condition, clearly indicating a reduction in the fouling potential of the mixed liquor in both strategies.

A possible explanation for the significant improvement in the filterability of the mixed liquor is that the aluminum compounds

Table 5 – Average values of modified fouling index, diluted sludge volume index, and supernatant turbidity with and without the application of electric current in both experimental strategies.

Strategy	Experimental Condition	MFI ($s\ mL^{-1}$)	DSVI ($g\ mL^{-1}$)	Supernatant turbidity
S1	No current application	3.3±0.8	135.0±7.2	23.6±15.3
	Intermittent current application	2.2±0.5	154.5±5.5	11.1±1.6
S2	No current application	2.7±0.6	269.1±55.2	54.9±12.5
	Continuous current application	1.5±0.2	289.4±17.6	15.7±0.8

MFI: modified fouling index; DSVI: diluted sludge volume index.

generated through anodic oxidation can destabilize colloids and negatively charged soluble substances, facilitating floc formation (Asif et al., 2020). Follmann et al. (2020), in their study with an e-MBR applied to wastewater treatment, concluded that the increase in floc size due to electrochemical processes resulted in reduced membrane fouling. Yan et al. (2012), in a study evaluating the application of polyaluminum chloride in an MBR for textile wastewater treatment, found that the coagulant application reduced the fouling potential of the mixed liquor by about 50%, highlighting the important role of the coagulation process in fouling control.

Additionally, according to Hua et al. (2015), the application of electrochemical processes can also result in the generation of oxidants, which can break down proteins and carbohydrates, directly related to fouling, into compounds with lower molecular weight, increasing their biodegradability and contributing to the reduction of their concentration in the mixed liquor. Similarly, Ibeid et al. (2013), when applying current densities between 15 and 35 $A\ m^{-2}$ with intermittent exposure modes, emphasized an improvement in mixed liquor filterability of up to 4.8 times. These authors claimed that currents higher than 15 $A\ m^{-2}$ are more effective in increasing mixed liquor filterability due to the greater dewatering capacity of the flocs under this condition. In the present study, the applied current density was 20 $A\ m^{-2}$ in both experimental strategies. However, in S2, the exposure mode was continuous, which explains the more significant improvement in filterability in this strategy compared to S1, where the application was intermittent (6 min on / 30 min off).

The DSVI is widely used to assess the sedimentability of activated sludge and is considered a crucial parameter in the operation of such systems. However, this test can also serve as an important indicator of mixed liquor filterability in MBRs. Sun et al. (2007) found that higher DSVI values can be associated with greater filtration difficulty. However, in this study, an increase in DSVI values was observed in both conditions after the application of electric current. This result was unexpected as the mixed liquor filterability was improved under these conditions, as evidenced by the MFI results.

According to Metcalf and Eddy (2014), activated sludge sedimentation can occur through different mechanisms, among which flocculent sedimentation (Type II) stands out, where particles agglomerate during the gravitational sedimentation process, with their size and velocity increasing over time; and delayed or zonal sedimentation (Type III), in which particles tend to remain in fixed positions and the mass settles as a unit (blanket). Therefore, a possible explanation for the increase in DSVI after the application of electric current is that, while the Type II sedimentation mechanism may have been enhanced by the electrocoagulation mechanism, contributing to the improvement in filterability, the Type III sedimentation mechanism may have been impaired due to the difficulty of the flocs remaining in a fixed position and settling as a blanket.

Finally, it is noteworthy that the supernatant turbidity, collected during the DSVI test, was substantially reduced after the application of electric current in both experimental strategies. In S1, the observed reduction was approximately 53%, while in S2, it was around 71%. These results corroborate the previously indicated trends and suggest an effective capacity for removing colloidal compounds in the mixed liquor, which are generally associated with membrane fouling (Du et al., 2020). Mollah et al. (2004) stated that the Al^{3+} ion reacts with free OH^- in water, forming, at near-neutral pH, several cationic complexes such as $Al(OH)_2^+$ and $Al_2(OH)_2^{4+}$. These formed compounds are highly effective in removing negatively charged organic materials due to their high charge neutralization capacity. Additionally, they exhibit a large surface area, capable of adsorbing and capturing colloidal particles and soluble organic pollutants, forming flocs that can be easily removed from the liquid phase through separation processes (Sahu et al., 2014).

Given this context, it is important to emphasize that, despite the observed reduction in sedimentation capacity, the mixed liquor filterability was improved under conditions with electric current application in both strategies, highlighting the potential of electrochemical processes to enhance MBR performance.

Conclusions

The intermittent application of electric current did not result in significant changes in the mixed liquor solids content. In contrast, when applied continuously, it led to an increase in FSS, attributed to the accumulation of insoluble compounds. Consequently, the SSV/TSS ratio remained below the recommended value for the operation of biological reactors.

The evaluation of true color and dye removal indicated that the application of electric current significantly improved efficiency in both strategies, highlighting the potential of electrocoagulation for this purpose. Similarly, phosphorus removal was also enhanced due to the occurrence of electrochemical processes. However, a slight reduction in ammoniacal nitrogen removal efficiency was observed under these conditions.

The mixed liquor exhibited a significant improvement in filterability after the application of electric current, especially when applied continuously. This effect was attributed to the presence of aluminum compounds, which promote the destabilization of colloids and soluble substances, reducing fouling potential. However, the unexpected increase in DSVI values suggests a deterioration in the sedimentation capacity of the mixed liquor.

Based on the obtained results, it is concluded that the application of electrochemical processes positively influences the characteristics of the mixed liquor, contributing to improved filterability. Additionally, this process can enhance pollutant removal, particularly phosphorus and dyes. Thus, this study contributes to a better understanding of the effects of electrochemical processes on mixed liquor, highlighting their potential as a complementary technology to optimize the performance and efficiency of biological systems in textile wastewater treatment, focusing on compliance with discharge standards and increasing reuse potential.

For future studies, it is recommended to conduct pilot-scale MBR tests to assess the long-term effects of electrochemical processes.

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Authors' Contributions

Battistelli, A.A.: conceptualization, data curation, formal analysis, investigation, methodology, supervision, validation, visualization, writing – original draft, writing – review & editing. **Zilch**, M.H.: formal analysis, investigation, methodology, writing – original draft. **Machinski**, J.H.S.C.: formal analysis, investigation, methodology, writing – original draft. **Gavlak**, G.: data curation, formal analysis, supervision, validation, visualization, writing – review & editing. **Pedroso**, C.R.: data curation, formal analysis, supervision, validation, visualization, writing – review & editing. **Souza**, K.V.: data curation, formal analysis, supervision, validation, visualization, writing – review & editing. **Souza**, J.B.: formal analysis, funding acquisition, project administration, resources, programs, supervision, validation, visualization, writing – review & editing. **Vidal**, C.M.S.: formal analysis, funding acquisition, project administration, resources, programs, supervision, validation, visualization, writing – review & editing.

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