



Research Paper

Evaluation of the Use of Reverse Osmosis in the Treatment of Galvanic Effluents

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Highlights

- Galvanic effluent was treated using two strategies.
- In strategy A, a reverse osmosis step was added to the end of the process.
- In strategy B, the ion exchange step was replaced by reverse osmosis.
- Both strategies were effective in treating the effluent, which complied with the regulations.
- Strategy A was more effective due to better performance and lower costs.

Abstract

The effluents from galvanotechnical processes contain toxic metals and recalcitrant substances. In the last few years, the restrictions on the quality of these effluents before release into the environment have intensified. A possible resolution for this problem is employing membrane separation processes, such as reverse osmosis, as a part/step in the treatment of this kind of effluent. This study aimed to analyze two strategies to enhance the performance of a galvanic treatment system. Strategy A was composed of physical-chemical treatment, advanced oxidation, simple filtration, and an ion exchanger, with the implementation of reverse osmosis in the existing process. Strategy B consisted of the substitution of the ion exchanger by reverse osmosis. It used a polysulfone RO membrane supported in polyamide. The efficiency of the proposed strategies regarding the environmental parameters for the disposal of the treated effluents was analyzed. The obtained results showed for strategies A and B removal of 99.45 % and 98.90 % for Ni, 99.96 % and 99.86 % for Cu, 99.77 % and 99.36 % for Zn, 98.16 % and 95.00 % for chemical oxygen demand, 94.13 % and 94.24 % for ammoniacal nitrogen, and 100% for total suspended solids, respectively. About 80-90 % of the starting transmembrane flux was restored in both strategies after chemical cleaning, but irreversible fouling also occurred. Total blocking was the main fouling mechanism observed, regardless of the strategy. The effluents treated using both strategies complied with the environmental parameters for the disposal of galvanic effluents, allowing for the substitution of a step in the process (strategy B). However, strategy A, due to the ion-exchange step, was more effective since it yielded lower final concentrations of heavy metals in the treated effluents. The ion-exchange step helps reduce the number of chemical cleanings and operational costs, increasing membrane lifespan, and reducing environmental impacts because of the smaller amounts of metal ions present in the treated effluent.

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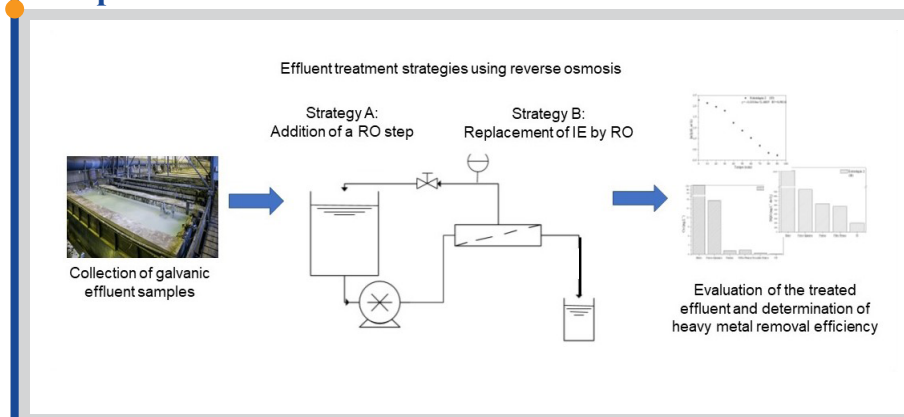
1. Introduction

Electroplating is a process used in the coating industry of metallic or polymeric parts, aiming to increase resistance to corrosion and to improve the part finishing and aspect. This process is used to coat parts in the automotive industry, jewelry, household appliances, and decorative items [1, 2]. Although there are alternative and efficient processes with less and smaller environmental impacts, such as Physical Vapor Deposition and

Chemical Vapor Deposition processes, electroplating is still the most widely used process in these industries [3].

The electroplating process consists in depositing uniform layers of metal, adherent and ductile, on the substrate surface to impart improvements in mechanical properties such as an improvement in hardness, reduction of wear and friction, and protection of the substrate from weather and chemical attack [4, 5].

Graphical abstract



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The galvanic process consumes large amounts of water and energy, generating solid wastes, liquid effluents, and atmospheric emissions that must be treated before being released into the environment or reused [6].

Wastewater is a liquid effluent that can contain cyanide (CN^-), hexavalent chromium (Cr^{6+}), nickel (Ni^{2+}), zinc (Zn^{2+}), copper (Cu^{2+}), tin (Sn^{2+}), gold (Au^+), silver (Ag^+), cadmium (Cd^{2+}), organic compounds, surfactants, soluble solids, sediments among others, depending on the kind of galvanic bath employed. This kind of effluent must be treated to achieve compliance with current legislation [7].

Effluents can be treated by physical-chemical processes such as coagulation, flocculation, sedimentation or flotation, advanced oxidation, ion exchangers, or osmosis membranes to remove organic compounds and heavy metals present in solutions [8, 9].

Ion exchange is a promising technique with compact equipment, high efficiency, ease of operation, and operation at room temperature [5, 10]. The quality of the effluents treated with ion exchange is higher in relation to the physical-chemical processes since ion exchange can selectively remove dissolved ions. On the contrary, this process has limitations because the regeneration of ion exchange columns requires employing chemicals and large amounts of rinsing water [11].

The effluents from galvanic processes have high concentrations of heavy metals and other compounds such as organic substances, microorganisms, oxidizing substances, and suspended particles [12]. Membrane separation processes are promising alternatives in the treatments of this kind of effluent since they allow for the reduction/removal of contaminants, reduce the saline load and toxicity, and provide reused washing water through the treated effluent [13].

Reverse osmosis (RO) is a process used to remove dissolved salts and organic matter of low molar mass. This process depends on the rejection through physical-chemical interactions, solubility differences, and the diffusivity between the solute and solvent relative to the membrane [14, 15].

Petricin et al. [13] employed ultrafiltration (UF) followed by reverse osmosis (RO) in the treatment of galvanic industry effluents. The authors reported a complete removal of nickel, chemical oxygen demand, biochemical oxygen demand, and nitrogen compounds, considering the process highly effective in the treatment of galvanic effluents.

Ennigrou et al. [16], evaluating a tangential UF system associated with mineral adsorbents, reported removal of 75 % for Cu^{2+} and 93 % for Ni^{2+} . Katsou et al. [17], using submerged UF with mineral adsorbents, observed removal of 78 % for Zn^{2+} , using synthetic effluent. Meanwhile, Araújo [18], using mesoporous ultrafiltration membranes, reported recovery percentages of 35 % Fe^{2+} and 60 % Zn^{2+} from galvanic effluent.

Maher et al. [19] treated a binary solution of Pb^{2+} and Ni^{2+} with nanofiltration (NF) and observed Pb^{2+} and Ni^{2+} removal of 93 % and 86 %, respectively, at pH 5.5 and a transmembrane pressure of 6 bar. Al-Rashdi et al. [20] treated a multi-component solution with NF and reported removal percentages of 99 % Cd^{2+} , 89 % Mn^{2+} , and 74 % Pb^{2+} at pH 1.5 and a transmembrane pressure of 4 bar.

Using electro dialysis (ED) and real effluent containing heavy metals, Tzanetakis et al. [21] reported the removal of 90 % Ni^{2+} and 69 % Co^{2+} , while Benvenuti et al. [22] reported the removal of 95 % Ni^{2+} . In tests performed by Aljendeel et al. [23] with synthetic metal solutions and using a polyamide reverse osmosis membrane, it was observed removal efficiencies of 96.6 % Cu^{2+} , 95.7 % Ni^{2+} , and 98.2 % Zn^{2+} . The same authors observed that mass transport and metal rejection were directly associated with the reduction of

permeate flux over time caused by the development of polarization concentration and fouling. Gaikwad et al. [24] reported removal efficiencies of 94,99 % F^- and 99,97 % Cr^{6+} , while Ngo et al. [25], observed removal of 98 % of Cu^{2+} , Ni^{2+} , Fe^{2+} , and Cr^{6+} . On the contrary, in the study performed by Feini et al. [26] using wastewater, 97 % of Cl^- and SO_4^{2-} were removed from the treated effluent.

Arabi et al. [27] tested the use of both reverse osmosis and adsorption columns to treat industrial wastewater containing metal ions. The authors reported the removal of more than 95 % of the metal ions and total solids, chemical oxygen demand, and turbidity, rendering the treated effluent suitable for reuse and discharge into the environment. The same authors reported the formation of fouling as the process occurred.

According to Zhang et al. [28], reverse osmosis (RO) is regarded as one of the most effective membrane technologies to carry out the treatment of heavy metal-contaminated wastewater. However, using only RO in the treatment of effluents is unfeasible because of the characteristics of the wastewater, which will render the membrane unusable due to the formation of fouling and the physical-chemical conditions of the effluent (extreme pH, presence of solids, high salt content). In this sense, reverse osmosis can be envisaged as a latter treatment step, aimed to polish and make the treated effluents comply with the pertinent regulations [7, 28].

Considering that there are few works in the literature addressing the addition of reverse osmosis to an industrial wastewater treatment process, the present work aimed to evaluate the impact of adding a reverse osmosis step (strategy A) or replacing the ion exchange step with reverse osmosis (strategy B) on the quality parameters of Cu^{2+} , Ni^{2+} , Zn^{2+} , N-NH_4^+ , chemical oxygen demand (COD), and total suspended solids (TSS) of the treated effluents and the effect of each strategy on the hydraulic permeability and fouling blocking model in the RO membrane.

2. Materials and methods

Fresh effluent samples were collected in February 2018 at a galvanic effluent treatment center located in the municipality of Guaporé, RS (geographical coordinates 28°52'27" S and 51°53'45" W). The obtained samples were treated immediately after collection, following the steps presented in Fig. 1.

The last step of traditional galvanic wastewater treatment is composed of an ion exchange process. In this work, after the treatment steps presented in Fig. 1, the galvanic waste was treated following two different strategies. In strategy A, a reverse osmosis step was added to the treatment scheme after the ion exchange process as the final step. In strategy B, the ion exchange step was replaced by reverse osmosis. A flowchart showing the steps of effluent treatment following both strategies is presented in Fig. 2.

The RO membrane used in the tests was a Metagoal® TFC-2002-100G membrane, with a support layer of polysulfone and a selective layer of polyamide, a useful area of 0.35 m² area, and an average pore size of 0.1 nm, operating at 23±2 °C and with a transmembrane pressure of 5 bar, with a processing time of 3 h (180 min). To restore membrane flow, the chemical cleaning was performed by washing with 0.08 M citric acid (pH 2) for 30 min, rinsing with distilled water for 30 min, washing with 0.025 M NaOH solution (pH 12) for 30 min, and rinsing with distilled water for 30 min. All cleaning steps were carried out at 30 °C.

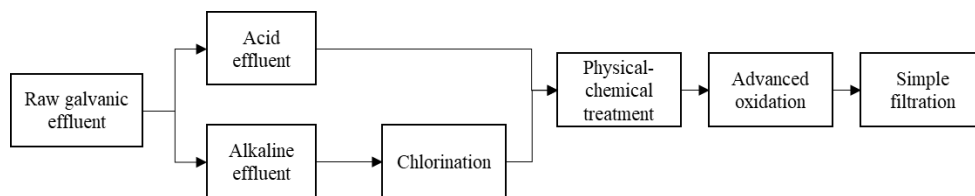


Fig. 1. Steps of galvanic waste treatment carried out before the treatment using reverse osmosis.

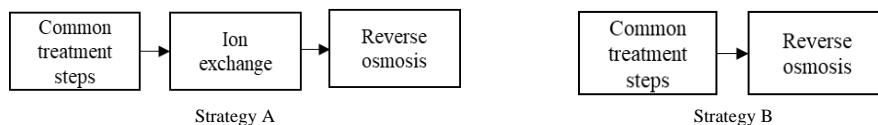


Fig. 2. Flowchart showing the treatment steps of galvanic effluent following strategies A and B.

The hydraulic permeability of the membrane as a function of the cleaning process was determined in both strategies, as well as the evaluation of the probable mechanism for flux reduction as the filtration progressed. The RO tests were carried out using the system described in Fig. 3.

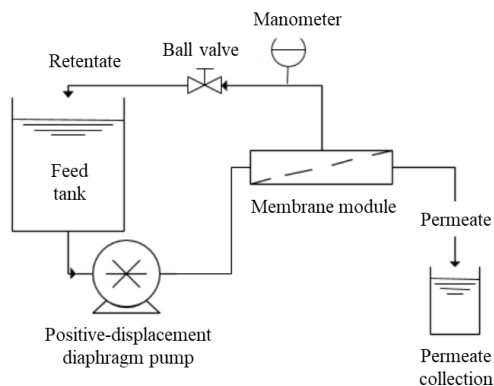


Fig. 3. Reverse osmosis system used in the experiments.

The hydraulic permeability was determined from experiments using distilled water at a constant temperature of 28 ± 2 °C. This parameter was evaluated at a pressure range of 0.5 – 6.0 bar in the RO membrane for both experiments, considering a membrane length of 20 cm, a specific mass of water of $1,000 \text{ kg}\cdot\text{m}^{-3}$, and a dynamic viscosity of $8.33 \times 10^{-6} \text{ Pa}\cdot\text{s}$.

After, the treated effluents were analyzed regarding the quality parameters for environmental purposes. The parameters of Cu^{2+} , Ni^{2+} , Zn^{2+} , N-NH_4^+ , chemical oxygen demand (COD), and total suspended solids (TSS) were analyzed. Copper, nickel, and zinc contents were determined following the SMEWW method 3030-W/3111-B, COD was determined according to the SMEWW method 5220-B, N-NH_4^+ was determined using the SMEWW method 450- NH_3 -B-C, and TSS content was determined following SMEWW method 2540-D.

The experiments were carried out in triplicates. The quality parameters of the effluent after treatment using both strategies underwent analysis of variance (ANOVA), followed by Fisher's least significant difference (LSD) test at 5 % error probability ($p = 0.05$). The statistical analysis was carried out using the Statistica 12 software (Statsoft, USA).

3. Results and discussion

3.1. Effect of each strategy on the quality of treated galvanic wastewater

The obtained results of quality parameters of the galvanic effluent samples treated following strategies A and B are presented in Table 1.

It is possible to observe that both strategies were highly effective in removing Ni^{2+} from the effluent, with removal efficiencies of 99.45 % and 98.90 % for strategies A and B, respectively, starting from an initial Ni^{2+} concentration of $9.51 \text{ mg}\cdot\text{L}^{-1}$. However, strategy A had a final Ni concentration statistically lower than strategy B.

Similar results for Ni^{2+} rejection using reverse osmosis are also reported. Ipek [29] observed 99.7 %, Mohsen-Nia et al. [30] reported 99.5 %, Aljendeel et al. [23] reported 98 %, Zhao et al. [31] observed 93 %, Ngo et al. [25] cited 95.7 %, He et al. [32] reported 94 %, and Petrinic et al. [13] reported complete removal (100 %), all using synthetic solutions containing nickel salts. Samaei et al. [33], using reverse osmosis in the treatment of raw effluent, observed a Ni^{2+} removal of 82 %.

These results show that the values found by the authors in the present study with raw galvanic effluent agree with those reported in the literature. As observed by Innocenzi et al. [11], the selectivity in the removal of heavy metal ions is associated with the affinity between the different species present in the solution and the material of the selective layer of the membrane since the transport occurs by diffusion following chemical sorption.

According to state legislation [34], the state environmental agency (FEPAM – Henrique Luis Roessler State Environmental Protection Foundation – RS) set the maximum value of $1.0 \text{ mg}\cdot\text{L}^{-1}$ total nickel in the effluent to be released to the environment. Thus, both strategies comply with the legislation, considering that the final Ni^{2+} concentration was below the maximum value ($0.052 \text{ mg}\cdot\text{L}^{-1}$ and $0.104 \text{ mg}\cdot\text{L}^{-1}$ for strategies A and B, respectively).

Regarding copper contents, strategy A had a Cu^{2+} removal efficiency of 99.96 %, with a final concentration of $0.047 \text{ mg}\cdot\text{L}^{-1}$ in the treated effluent, whereas in strategy B the removal was 99.86 %, with a final Cu^{2+} concentration of $0.171 \text{ mg}\cdot\text{L}^{-1}$, which were statistically different. This result is associated with the interaction between the organic molecules and the ion pairs formed in the solution, causing a change in the size of the ion hydration layers and their complexation. The hydration radius of the $[\text{Cu}(\text{H}_2\text{O})_6]^{2+}$ ion copper hexahydrate is 4.24 \AA , greater than the membrane pore diameter [35].

In other studies using synthetic solutions containing Cu^{2+} and using polyamide reverse osmosis membranes, Qdais et al. [36] observed a removal efficiency of 97 %, Ngo et al. [25] reported 98 %, You et al. [37] observed 94 %, and Vital et al. [38] observed 98.9 %. Makisha [39] applied reverse osmosis to treat raw effluent and reported a Cu^{2+} removal efficiency of 98 %. These authors also commented that reverse osmosis, with or without previous treatment steps, is highly efficient in removing Cu and other heavy metals. However, without previous treatment, most RO systems would become unusable shortly when treating real galvanic effluent.

The Rio Grande do Sul state legislation [34] established a maximum total copper content in the effluent of $0.5 \text{ mg}\cdot\text{L}^{-1}$, to be considered suitable to be released into the environment. The effluents treated following strategies A and B had final Cu^{2+} concentrations of $0.047 \text{ mg}\cdot\text{L}^{-1}$ and $0.171 \text{ mg}\cdot\text{L}^{-1}$, respectively, values well below the maximum established by the legislation.

Relative to zinc, strategy A, yielded a final Zn^{2+} concentration of $0.094 \text{ mg}\cdot\text{L}^{-1}$, with a removal efficiency of 99.77 % in relation to the raw effluent. With strategy B, the Zn^{2+} concentration was $0.266 \text{ mg}\cdot\text{L}^{-1}$ with a removal efficiency of 99.36 % relative to the raw effluent. Zinc concentration in strategy A was statistically lower than in strategy B. The final Zn^{2+} concentrations observed using strategies A and B were $0.094 \text{ mg}\cdot\text{L}^{-1}$ and $0.266 \text{ mg}\cdot\text{L}^{-1}$, respectively, below the maximum value established by the legislation, which is $2.0 \text{ mg}\cdot\text{L}^{-1}$.

This rejection is associated with interactions between the ions and organic molecules and ligands present in the effluent and the formation of ion pairs. This results in changes in the hydration layer size and ion complexation. The $[\text{Zn}(\text{H}_2\text{O})_6]^{2+}$ zinc hydration radius is 2.08 \AA , larger than the membrane pore diameter [40]. However, considering that RO membranes are mostly non-porous, changes in the hydration layer would only influence if the membrane had imperfections and/or undesired pores within it.

Table 1
Results of the quality parameters for the galvanic effluent treated with both strategies.

Parameter	Concentration in raw effluent ($\text{mg}\cdot\text{L}^{-1}$)	Final Concentration		Removal		Maximum concentration ¹ ($\text{mg}\cdot\text{L}^{-1}$)
		Strategy A ($\text{mg}\cdot\text{L}^{-1}$)	Strategy B ($\text{mg}\cdot\text{L}^{-1}$)	Strategy A (%)	Strategy B (%)	
Cu	129.2	0.047 b	0.171 a	99.96	99.86	0.5
COD ²	2,398	44 b	96 a	98.16	95.00	330
Ni	9.51	0.052 b	0.104 a	99.45	98.90	1
N-NH ₄ ⁺	54.07	3.17 a	3.11 a	94.13	94.24	20
TSS ³	590	*	*	100	100	200
Zn	40.68	0.094 b	0.266 a	99.77	99.36	2

¹ – According to CONSEMA 355/2017 regulation [34]. ² – Chemical oxygen demand. ³ – Total suspended solids. * – below the limit of detection ($0.7 \text{ mg}\cdot\text{L}^{-1}$). Means in row followed by the same letter do not differ by Fisher's LSD test at 5 % error probability ($p = 0.05$).

Kamar et al. [41] reported Zn²⁺ removal efficiency of 96.29 % while Samaei et al. [33] reported 48 %, both using reverse osmosis. Using synthetic solutions containing Zn²⁺, Aljendeel et al. [23] reported a removal efficiency of 98.2 %, You et al. [37] reported 94 %, and Vital et al. [38] reported 99.5 %. As commented previously, while RO is highly effective in the removal of heavy metals, its efficiency is highly dependent on feed characteristics and composition.

The removal of COD by reverse osmosis was satisfactory in both strategies. In strategy A the obtained removal of COD was 98.16 %, with a final concentration of 44 mg·L⁻¹, while in strategy B the COD removal was 95.00 %, with a final concentration of 96 mg·L⁻¹. Statistically, strategy A yielded lower COD values after treatment than strategy B.

In similar studies, Feini et al. [26] reported a COD removal of 78.9 %, while Song et al. [42] reported 86.9 %, and Petrinic et al. [13] reported complete (100 %) removal from wastewater using a polyamide reverse osmosis membrane. Regarding the state standards, the COD removal results were satisfactory, considering that the legislation establishes a maximum flow of 100 m³·day⁻¹, with a maximum COD load of 330 mg·L⁻¹.

It is important to observe that most of the COD present in galvanic effluents are from the ligands and organic additives (detergents, stabilizers) used in the process, which are large molecules, whose diffusion through the membrane tends to be hindered. However, the interaction between membrane polymer and these organic compounds can also help their sorption, enhancing diffusion, which may explain the presence of residual COD in some systems and its absence in others [13, 26, 42].

Both strategies were adequate in the removal of N-NH₄⁺, with no statistical difference between the strategies. In strategy A, the removal efficiency was 94.13 %, while in strategy B the removal efficiency was 94.24 %, with final concentrations of 3.17 mg·L⁻¹ and 3.11 mg·L⁻¹, respectively. Both strategies complied with state legislation [34], which fixes N-NH₄⁺ discard at the maximum concentration of 20 mg·L⁻¹.

Hurtado and Cancino-Madariaga [43] reported removal efficiencies above 98 % when testing reverse osmosis and nanofiltration membranes in the removal of ammonium ions from water, and Petrinic et al. [13] reported complete removal. According to Sengupta et al. [44], membrane separation processes that rely on sorption-diffusion mechanisms, such as nanofiltration and reverse osmosis, are highly efficient in the retention of nitrogen and phosphorous in wastewater due to the larger anion sizes relative to the cations.

Regarding TSS content, the results obtained in strategies A and B were of complete (100 %) removal. Similar results were obtained by Petrinic et al. [13]. The complete removal of TSS was due to the barrier effect characteristic of

dense membranes, such as those of reverse osmosis [45]. Considering that the legislation stipulates a maximum effluent flow of 100 m³·day⁻¹ with a maximum TSS value of 140 mg·L⁻¹, both strategies were suitable for the removal of any suspended material due to the intrinsic properties of reverse osmosis.

Considering that suspended solids have particle sizes in the micrometer range, even if the membrane presents some pores, the size of the particles prevents them from passing the membrane. On the other hand, large amounts of TSS will cause fouling in the membrane by cake formation, hindering diffusion and reducing the transmembrane flux, with deleterious effects on membrane performance [45, 46].

Considering the composition of the treated effluents, both strategies would comply with the environmental regulation of Rio Grande do Sul state. However, considering that strategy A employed an ion-exchange step followed by RO, and strategy B used a sole RO step, it is important to point out that while RO may be aimed to ‘polish’ the treated effluent, it can also help maintain the quality of the effluent when the ion-exchange step loses efficiency or the ion-exchange resins saturate. In this sense, a coupled process may be more interesting to keep process robustness and by decreasing the overall strain on both systems, especially the RO membrane, especially when considering a sole RO step (strategy B).

3.2. Hydraulic permeability and membrane resistance mechanism in each strategy

The results of the hydraulic permeability of the RO membrane with an operation time of 180 min for both strategies are presented in Fig. 4.

According to Fig. 4, it was possible to observe that strategy A had a better performance regarding hydraulic permeability, with better conditions of scaling up with a longer process time and a lower transmembrane flux. This may also represent a greater membrane lifespan due to fewer maintenance stops for chemical cleaning and, consequently, more operation time for the equipment. The lower transmembrane flux between the strategies may also be a direct effect of the prior ion exchange step in strategy A, which would limit the feed to RO step, while in strategy B the collected wastewater went directly to RO, which may also explain the quick reduction in transmembrane flux (from 8.5 L·m⁻²·h⁻¹ to about 1.5 L·m⁻²·h⁻¹ after 50 min of operation – a reduction of 82.35 % of the initial flux).

The results of chemical cleaning and membrane permeability are presented in Fig. 5.

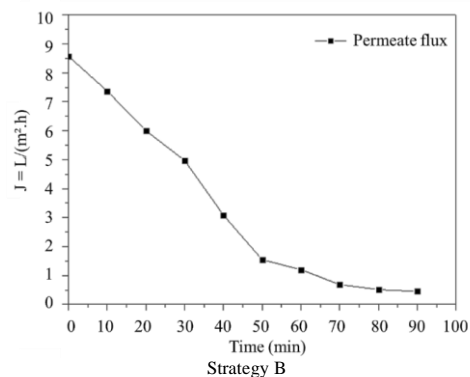
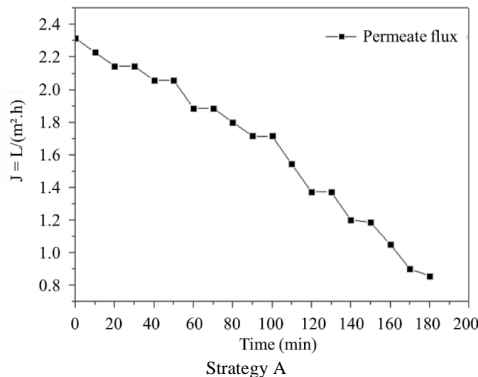


Fig. 4. Reduction of the hydraulic permeability of the membrane as a function of process time for both tested strategies.

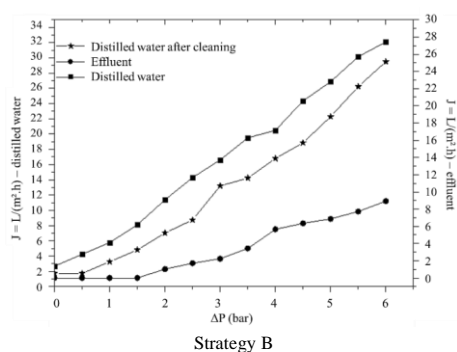
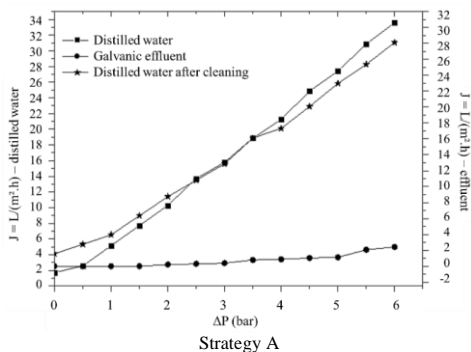


Fig. 5. Transmembrane fluxes as a function of transmembrane pressure in both strategies, using distilled water and effluent.

In both strategies, the permeate flux had a linear relationship when using distillate water and the galvanic effluent up to 6 bar, with a reduction of 93.12 % of the transmembrane flux in strategy A, and 71.75 % in strategy B, suggesting the presence of interaction effects between the effluent and the membrane. With the concentration of the feed, the dynamic viscosity increased, affecting the concentration polarization resistance and increase in boundary layer thickness.

After the steps of chemical cleaning, the permeate flux was restored to 83.66 % of the starting transmembrane flux in strategy A, while for strategy B the restored flux was 92.98 % of the starting flux. This also suggests the occurrence of irreversible fouling since the flux was not completely restored. Kurt et al. [47], observed similar behavior in the nanofiltration and reverse osmosis of textile effluents using a polyamide membrane. In this work, the starting flux decreased from 51 L·m⁻²·h⁻¹ to 7 L·m⁻²·h⁻¹ after 800 min of operation, observing a flux recovery of 75 % relative to the starting flux after chemical cleaning. Andrade et al. [48] also observed this phenomenon by testing a nanofiltration system in the treatment of gold mining effluent, with a reduction of 80 % of the flux during operation, and 70 % recovery.

In this sense, while the occurrence of irreversible fouling cannot be avoided completely, both strategies suggest that chemical cleaning can restore most of the starting flux in both conditions, rendering the process viable in both strategies. However, regarding the overall performance, strategy A had a better flux restoration than strategy B, indicating that the presence of the ion exchange step helps keep membrane performance and reduces the fluctuations in feed composition inherent to the effluent.

Different resistances are involved in reverse osmosis, in both strategies. The reduction in transmembrane flux is related mainly to polarization concentration, contributing to 86.2 % of the total resistance observed in strategy A. For strategy B, fouling was the main resistance observed, representing 36.6 % of the total resistance. Andrade et al. [48] observed polarization concentration as the major resistance component for nanofiltration membranes, corresponding to 40 % of total resistance.

The increase in polarization concentration is related to the amount of solute near the membrane surface, within the boundary layer. The concentration gradient near the surface induces a back diffusion to the bulk of feed, hindering transmembrane diffusion and reducing transmembrane flux. When the polarization concentration is severe, the membrane also becomes prone to fouling, reducing even more transmembrane flux, and increasing the probability of irreversible fouling [49, 50].

The coefficients of determination for the different blocking mechanisms tested following the Hermia model [51] are presented in Table 2.

Table 2
Coefficients of determination (R^2) for the different blocking mechanisms proposed by the Hermia model using galvanic effluent in the RO process.

Strategy	Cake formation	Intermediate blocking	Standard blocking	Total blocking
A	0.8378	0.7442	0.8798	0.9163
B	0.8117	0.6030	0.9180	0.9774

A – reverse osmosis after ion exchange. B – reverse osmosis replacing ion exchange.

According to the coefficients of determination observed for the different blocking mechanisms tested according to the Hermia model, fouling occurred in the RO steps in both strategies. According to the resistance model, total blocking had the best relationship with the experimental data of both strategies, followed by standard blocking. This indicated that the flux reduction mechanism is similar for both strategies, with little to no influence of the presence of the ion exchange step on the development of fouling and reduction of transmembrane flux for the observed membrane.

Considering that the total blocking mechanism is characterized by particles closing some pores at the membrane surface, most of the fouling can be attributed to TSS, COD, and molecules associated with $N-NH_4^+$ in the effluent. The second mechanism observed in standard blocking can be associated with the metal ions because in standard blocking the particles interact with membrane pores and imperfections and are adsorbed on pore/imperfections walls, probably through a chemical reaction (irreversible fouling) suggesting that both the organics load and the metal ions influence membrane performance and metal rejection effectiveness [46,51].

4. Conclusion

The addition of a reverse osmosis step in both strategies yielded treated effluents with quality and characteristics in compliance with the state regulations for galvanic effluents, and with final concentrations well below the maximum allowed concentrations. Although both strategies had excellent performances regarding effluent treatment, strategy A was more effective, as it showed lower final concentrations of the analyzed components. Although longer system uptime was required, it reduced the number of chemical cleanings and operational costs, increasing the lifespan of the membrane and reducing the maintenance time of the system. Regarding system cleaning and flux reduction mechanisms, about 80 – 90 % of the starting transmembrane flux was restored in both strategies, but irreversible fouling also occurred. In addition, the fouling mechanism of total blocking was observed in both strategies. Thus, the addition of a reverse osmosis step in the treatment of galvanic effluents can be an alternative to help polish the treated effluents, also being possible to reuse them as rinsing water due to the low concentrations of metals and other contaminants.

CRedit authorship contribution statement

R. Zelinski: Conceptualization, Investigation, Writing – original draft.
W.P. Silvestre: Formal analysis, Methodology, Investigation, Writing – original draft.
J. Duarte: Data curation, Investigation, Writing – review & editing.
N.F. Livinalli: Investigation, Writing – review & editing.
M. Zeni: Methodology, Supervision, Writing – review & editing.
C. Baldasso: Conceptualization, Formal analysis, Writing – review & editing, Resources, Supervision, Project administration.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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