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Chromium Removal from Real Tannery Wastewater by Electrocoagulation Assisted with Prickly Pear (*Opuntia* spp.) Cladode Powder

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Abstract. This study investigated the performance of electrocoagulation (EC) coupled with prickly pear cladode powder (PPP) for removing chromium from real chrome-tanning wastewater. Experiments were performed in a batch stirred electrocoagulation cell equipped with two aluminum-based electrodes. The effects of treatment time, current density, initial pH and PPP dosage were examined, with the experiments performed in triplicate using the same wastewater sample. The wastewater initially contained 3.60 g L^{-1} of chromium (3,600 mg L^{-1}). Optimum conditions were found to be an initial pH of 7.02, a PPP dosage of 20.00 g and a current density of 200 A m^{-2}. Under these conditions, a treatment time of approximately 200 minutes reduced the chromium concentration to 2.00 mg L^{-1}, corresponding to a removal efficiency of around 99.90 %. Compared with EC alone, the EC/PPP process improved chromium removal performance while reducing energy consumption. The specific energy consumption was 3.00 kWh m^{-3} for EC and 1.50 kWh m^{-3} for EC/PPP, representing a 50.00 % reduction in energy usage. These results demonstrate that adding prickly pear cladode powder enhances chromium removal and substantially decreases the electrocoagulation process's energy requirements, highlighting the EC/PPP process's potential for treating highly concentrated chrome-tanning wastewater.

Keywords: *Prickly pear cladode powder, Chromium, Electrocoagulation, Adsorption, Energy consumption.*

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Introduction

In Morocco, the excessive use of water by industry and the discharge of untreated liquid waste into the environment have become major concerns. Excessive water consumption remains a common practice in several industrial sectors, putting significant pressure on already limited water reserves. A lack of suitable equipment for treating liquid discharges means that a large proportion of effluent is discharged directly into the environment, leading to the significant pollution of rivers, soils and groundwater. The deterioration of water resources exacerbates the water availability crisis, disrupts ecological balances and endangers human health. In this context, implementing rational and sustainable water management practices supported by more efficient treatment technologies is essential (Netherlands Enterprise Agency, 2018).

One of the main environmental issues in the leather processing sector concerns the management of effluents from chrome tanning processes. These processes generate waste containing various heavy metals, the most notable of which is chromium due to its chemical reactivity and potential toxicity. This metal, in its various forms, is recognized for its harmful effects on aquatic organisms and the health risks it poses to humans, as well as contributing to the degradation of surrounding ecosystems. Uncontrolled discharge of this waste into the environment can cause profound ecosystem alterations, including the contamination of surface and groundwater, soil degradation, and disruption to biogeochemical cycles. In this context, implementing advanced treatment processes alongside strict regulatory frameworks is essential to minimize the environmental impact of tanning activities and ensure the long-term preservation of natural resources and public health.

Using natural waste for wastewater treatment is an innovative and effective method with positive economic and environmental impacts. Prickly pear cladode powder is one such sustainable adsorbent that can be used to treat polluted water. Research has shown that this mucilage-rich powder has excellent flocculant and adsorbent properties, enabling the effective removal of suspended particles and various pollutants. Studies by Miller *et al.* (2008) have proven the effectiveness of cactus mucilage as a bioflocculant in treating domestic wastewater, achieving a significant reduction in suspended solids. Adjeroud *et al.* (2018) confirmed its effectiveness as a natural coagulant in water purification processes. Nogueira *et al.* (2009) studied the use of cactus-derived materials in treating industrial effluents and achieved promising results in removing heavy metals such as copper and chromium.

In recent years, the use of the natural coagulant *Opuntia ficus-indica* in electrochemical methods such as electrocoagulation-electroflotation (EC-EF) has attracted increasing interest (Adjeroud *et al.*, 2015; Adjeroud *et al.*, 2018; Adjeroud-Abdellatif *et al.*, 2020; Djerroud *et al.*, 2018; Djerroud-Mohellebi *et al.*, 2023). For example, Adjeroud *et al.* (2018) emphasized the significant potential of *Opuntia ficus-indica* cladode mucilage for decontaminating wastewater. It was found to be highly effective in removing copper, achieving 100 % efficiency when added to the electrocoagulation-electroflotation process. Furthermore, *Opuntia ficus-indica* cladode juice has been shown to be effective in removing suspended particles, with enhanced turbidity removal noted when the natural flocculant is combined with EC-EF (86.90 % removal efficiency after response surface methodology optimization), compared to conventional EC-EF, which achieves only 71.90 % turbidity removal (Adjeroud *et al.*, 2015).

Figueirôa *et al.* (2021) demonstrated the effectiveness of *Opuntia ficus-indica* as a natural biosorbent for removing chromium, validating its potential for the sustainable treatment of industrial effluents. Furthermore, Meftah *et al.* (2023) demonstrated the strong potential of cactus-based powdered bioflocculants for improving wastewater treatment. Laboratory tests revealed high removal efficiencies for turbidity, suspended solids, organic matter, dyes, and heavy metals, often surpassing 90.00 % under favorable conditions. The results also highlighted the influence of key parameters such as dosage, pH and contact time, confirming the stability and practicality of the solid form. Overall, this body of work reinforces the relevance of cactus-derived materials as a natural and sustainable option for treating both domestic and industrial wastewater.

The novelty of this work lies in its combination of the direct use of prickly pear cladode powder (PPP), the treatment of real chromium-containing tannery wastewater and the simultaneous evaluation of pollutant removal performance and energy consumption. This combination has received limited

attention in existing literature. Against this background, using prickly pear cladode powder as an adjunct to conventional aluminum electrocoagulation (EC) is a promising approach for enhancing chromium removal. Unlike PPP alone, direct application of the powder may provide additional coagulation and adsorption mechanisms due to the presence of bioactive and surface-active components in the plant material. This combination is particularly relevant for chromium-containing tannery effluents, where the complexity and high pollutant load of the wastewater may limit the performance of conventional EC alone. Despite growing interest in prickly pear cladode powder-based materials for wastewater treatment, little attention has been given to their direct integration into EC for treating real chromium-rich tannery wastewater. In this context, the present study investigates the combined use of aluminum electrocoagulation and prickly pear cladode powder for treating real tannery wastewater containing an initial chromium concentration of 3.81 g L^{-1}. The specific objectives were to: (i) assess the effect of cladode powder addition on the operational performance and chromium removal efficiency of the EC process; (ii) determine the optimal operating conditions by evaluating the effects of treatment time, cladode powder dosage and current density; and (iii) assess the energy consumption associated with the treatment process under optimized conditions.

Materials and Methods

Effluent sample

The samples used in this study were obtained from a chromium-tanning tank in a small, semi-traditional tannery in the city of Marrakech, with a treatment capacity of around 500 skins per day. Electrical conductivity (1:5 w/v soil-water suspensions) and pH (1:2.5 w/v soil-water suspensions) were measured using a multiparameter LF 92 WTW probe. Available phosphorus (P_2O_5) was determined using the Olsen method (Olsen and Sommers, 1982), and total Kjeldahl nitrogen (TKN) was determined using the Kjeldahl method (Bremner, 1996). Major and trace element analyses were conducted using X-ray fluorescence spectrometry (Olympus, UK) and an atomic absorption spectrophotometer (Shimadzu AA-6300), respectively. Heavy metal concentrations were determined following the total digestion of 0.50 g of dry mine tailings at 500 °C. The sample was digested in a Teflon beaker containing 7 mL of nitric acid (HNO_3) (65.00 % w/w), 2 mL of hydrofluoric acid (HF) (40.00 % w/w) and 1 mL of perchloric acid ($HClO_4$) (60.00 % w/w). The resulting solution was filtered using a 0.45 µm cellulose nitrate filter, and the volume was adjusted to 10 mL with 0.1 M HNO_3. The chromium calibration curve was prepared using standard solutions from Prolabo (France).

The removal efficiency (Re %) of each chromium was calculated using the following equation [1]:

$$Re(\%) = \frac{C_0 - C_f}{C_0 66} \times 100 \quad [1]$$

where C_0 and C_f represent the initial and the final concentrations respectively.

Material sample

In May 2016, cladodes of the Opuntia species were collected from the Taguimalt region in southeastern Morocco. These cladodes, measuring approximately 15 – 20 cm in length and 1 – 2 cm in thickness, were manually cleaned to remove thorns, brown spots and other visible impurities. After air-drying the cleaned cladodes at room temperature for 48 hours, they were cut into small pieces and ground into a fine powder using a laboratory grinder. The resulting powder was sieved to obtain a

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homogeneous particle size; after which it was stored in a desiccator at room temperature until further use. This material was designated prickly pear cladode powder (PPP).

Experimental set-up

The electrochemical runs were carried out in a discontinuous treatment reactor by recirculating a volume of 2 L of water through a flow system consisting of a reservoir tank, a peristaltic pump and an electrochemical cell (Figure 1). The peristaltic pump (Masterflex L/S, USA) enabled fluid recirculation at a rate of up to 2000 mL min^{-1}. The electrocoagulation cell consisted of two identical polymethyl methacrylate halves (20 cm × 10 cm × 5 cm), each containing aluminum electrode plates (15 cm × 7 cm × 1.2 cm). The distance between the two electrodes remained constant at 1 cm throughout all experiments. For the combined EC/PPP experiments, the required dose of prickly pear cladode powder (PPP) was added directly to the wastewater in the reservoir tank prior to treatment commencement. After each run, a 2.00 % (v/v) solution of sulfuric acid is poured onto the surface of the electrodes. The electrodes' surfaces were manually polished with abrasive paper and rinsed with distilled water before each run. The effective electrolysis area of each electrode is 105 cm^2. The electrodes were connected to a laboratory DC power supply (EA-PS 3065-10 B, UK), which provides a current range of 0 – 10 A. The current used was held constant throughout the experimental runs. The reservoir tank was connected to a water-filled cylinder that was used to quantify the hydrogen released, principally from the cathode, during the runs. This cylinder was filled with tap water using a vacuum pump (Vacuubrand MZ2NT, Germany) prior to each run. Gentle mechanical agitation at 150 rpm was set up in the reservoir tank using an agitator control (EUROSTAR 60, IKA, France). Figure 1 shows the schematic diagram of the complete electrocoagulation system.

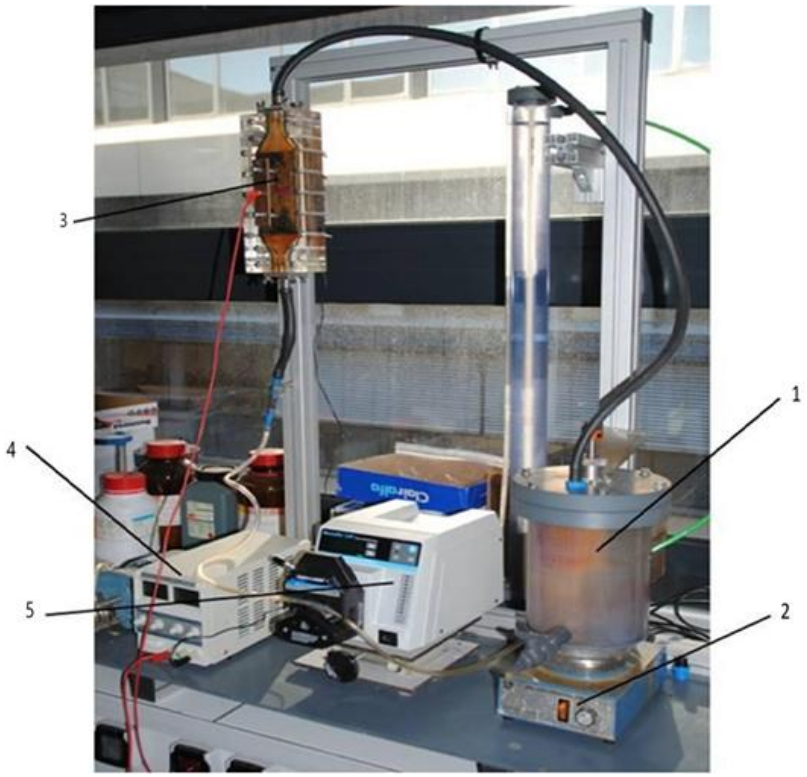


Figure 1. Experimental Electrocoagulation set-up. 1: Reservoir tank; 2: Mechanical agitator control; 3: Electrochemical Cell; 4: DC power supply; 5: Peristaltic pump.

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Experiments

Electrocoagulation experiments were conducted at an ambient temperature of approximately 20 °C, using 2 liters of wastewater. The wastewater was gently stirred at 200 rpm while a peristaltic pump maintained continuous recirculation through the flow circuit at a flow rate of 50 mL min^{-1}. The experiments were performed at the wastewater's natural pH, without any prior adjustment, to investigate treatment under actual industrial effluent conditions. Prickly pear cladode powder (PPP) was added at a dosage of 20.00 g L^{-1}, which was determined to be the optimal dosage in preliminary experiments.

Aluminum alloy A-U4G (2017-Al) was used for the sacrificial electrodes. This alloy contained Cu (4.00 %), Fe (0.70 %), Mg (0.70 %), Mn (0.70 %), Si (0.50 %), Zn (0.25 %) and Cr (0.10 %), with aluminum making up the rest. The electrodes were connected to a DC power supply (AFX 2930 SB, China). Current intensities ranging from 2.1 to 4.2 A (corresponding to current densities of 200 – 400 A m^{-2}) were applied and kept constant throughout each experimental run. The cell voltage was continuously monitored during the experiments. Ten-milliliter samples were collected at regular time intervals (every 10 minutes during the first hour, and then every 30 minutes). After collection, the samples were left to settle for 24 hours and were then filtered through a 0.45 µm membrane filter prior to analysis. The filtered samples were analyzed for COD, Cr(III) and Al(III) concentrations.

Energy consumption

The energy consumption was calculated in terms of kWh per kg of removed chromium to analyze the possible positive effect in this specific case of very concentrated effluents. This normalization was used to evaluate the energy efficiency of the treatment process, particularly for the highly concentrated effluents investigated in this study. It is estimated using the following equation 2:

$$EEC = \frac{UIt10^3}{60(C_0 - C_t)V} \quad [2]$$

where *U* is the cell voltage measured during the electrolysis (V), *I* the applied electrical current (A), *t* the current time of treatment (min), and *V* the reactor volume (L). C_0 and C_t are the initial chromium concentration and the concentration at time t (in mg L^{-1}). The term $(C_0 - C_t)V$ represents the mass of chromium removed during the treatment. The calculated electrical energy was subsequently normalized to the corresponding mass of chromium removed and expressed as kWh kg^{-1} Cr removed.

Results and Discussion

Physicochemical characteristics of raw wastewater

Wastewater samples were collected at the chrome tanning stage of the leather processing cycle. To ensure the representativeness of the characterization, three independent wastewater samples were collected under similar operating conditions. Each physicochemical parameter was analyzed in triplicate (n = 3) and the results, which are expressed as mean ± standard deviation (SD), are presented in Table 1. The analyzed parameters included pH, electrical conductivity, chloride, chemical oxygen demand (COD), sulphate and total chromium (Cr total). The initial total chromium concentration was approximately 3.6 g L^{-1}, highlighting the highly concentrated nature of the wastewater generated during chrome tanning. To facilitate comparison with regulatory requirements, the applicable discharge limits for the analyzed parameters are also included in Table 1.

Table 1. Main characteristic of tested raw wastewater.

Parameter	Value	SD	DL
pH (at 25 °C)	3.81	0.10	6.5-9
EC (mS/cm) (at 25 °C)	60.00	3.00	2.70
Cl^- (g L^{-1})	11.60	0.50	500.00
COD (g L^{-1})	3.75	0.10	0.20
SO_4^{2-} (g L^{-1})	1.60	0.20	45.00
Cr total (mg L^{-1})	3600.00	0.05	2.00

SD: Standard Deviation; **DL**: Discharge Limit

pH evolution during treatment

The pH of the solution plays an important role in the performance of the electrocoagulation and sorption processes, and changes in pH during treatment are linked to efficiency. The different forms of $Al(OH)_3$ present in the solution depend greatly on the pH and the concentration of Al^{3+} ions in the medium. This graph illustrates how the pH level varies over time during electrocoagulation, comparing treatments with and without the addition of prickly pear cladode powder. Initially, both processes start at a similar pH level of around 4. However, as the treatment progresses, an increase in pH is observed for both methods.

Electrocoagulation treatment alone results in a steady increase in pH, reaching approximately 6.09 after 120 minutes. In contrast, the combined electrocoagulation and prickly pear cladode powder treatment (indicated by hollow triangles) shows a similar upward trend, but maintains a slightly higher pH throughout, reaching approximately 7.02 after 120 minutes. This increase in pH in both treatments is attributed to the formation of hydroxide ions during electrolysis, which promotes the removal of heavy metals through precipitation, as demonstrated in previous studies (Chen, 2004; Sánchez-Silva *et al*., 2025). The higher pH observed in the presence of PPP aligns with the findings of Figueirôa *et al.* (2021) and Adjeroud *et al.* (2018), who reported that cactus-based materials can enhance alkalinity and improve the sorption efficiency of heavy metals such as chromium. These results are consistent with earlier research showing the synergistic effects of combining natural biosorbents with electrochemical processes to optimize wastewater treatment.

This study demonstrates that integrating prickly pear cladode powder (PPP) into the electrocoagulation (EC) process significantly improves the efficiency with which chromium is removed from wastewater. Notably, the combined EC/PPP process achieves higher pH values than EC treatment alone, with an increase in pH observed over time. This rise in pH is consistent with previous studies that emphasise the importance of alkalinity in enhancing the precipitation of heavy metals.

For example, Merzouk *et al.* (2009) reported a chromium removal efficiency of over 60.00 % at a pH of 7.80 at the beginning of the EC process. In our study, the EC/PPP process achieved comparable or even superior removal efficiencies more quickly. Adjeroud *et al.* (2018) found that adding *Opuntia ficus-indica* mucilage to the EC-EF process improved copper removal from wastewater. This approach is simple, inexpensive and environmentally friendly, demonstrating the potential of natural materials to improve traditional treatment methods.

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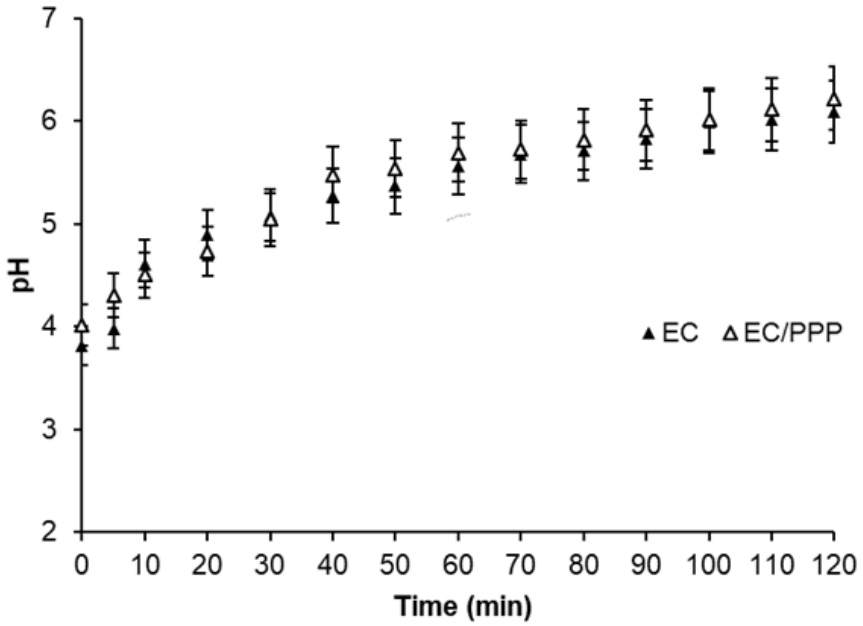


Figure 2. Variation of pH value during EC and EC/PPP coupling process.

This study emphasises the potential benefits of incorporating natural coagulants such as OFI mucilage into conventional wastewater treatment technologies, offering a more sustainable and efficient approach to heavy metal removal. These results contribute to the existing body of knowledge by confirming and expanding upon previous findings regarding the role of pH and natural coagulants in electrocoagulation processes.

Effect of current density

Current density is a crucial operational parameter in electrocoagulation (EC) processes since it affects the rate at which coagulant species are created, influences the generation rate and size of hydrogen and oxygen gas bubbles and consequently affects floc evolution and pollutant removal efficiency. In the present study, the impact of current densities of 200, 300 and 400 A m^2 on electrocoagulation (EC) and combined EC/prickly pear cladode powder (EC/PPP) treatments was evaluated. These current densities were maintained over treatment durations ranging from 5 to 360 minutes to evaluate short- and long-term performance under different operational conditions.

Analysis of table 2 and figure 3 reveals notable differences in chromium removal efficiency depending on the process used. Figure 3a, which corresponds to the EC process alone, shows progressive chromium removal as current density values increase, reaching nearly 100 % after approximately 300 minutes. Higher currents (400 A m^2) demonstrate faster and more efficient performance, whereas lower currents (200 A m^2) necessitate a longer treatment time. In contrast, figure 3b, representing the EC process coupled with prickly pear cladode powder, shows significant improvement. Chromium removal is faster, reaching almost 100 % in under 250 minutes. This improvement is evident even at lower current densities compared to the trial without flocculant addition (Figure 3a). This suggests that prickly pear powder acts as a natural flocculant, accelerating the flocculation of chromium particles and reducing the time needed to achieve maximum efficiency. Furthermore, this mitigates dependence on the applied current density, leading to reduced energy consumption.

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Table 2. Effect of current density on chromium removal by EC process alone (a), and by EC combined to prickly pear cladode powder (EC/ PPP).

Current density	Time of 50 % chromium removal		Time of 95 % chromium removal		Time of 98 % chromium removal	
	EC	EC/PPP	EC	EC/PPP	EC	EC/PPP
200 A m^2	110	70	270	120	240	130
300 A m^2	100	60	220	100	200	120
400 A m^2	90	60	180	90	160	110

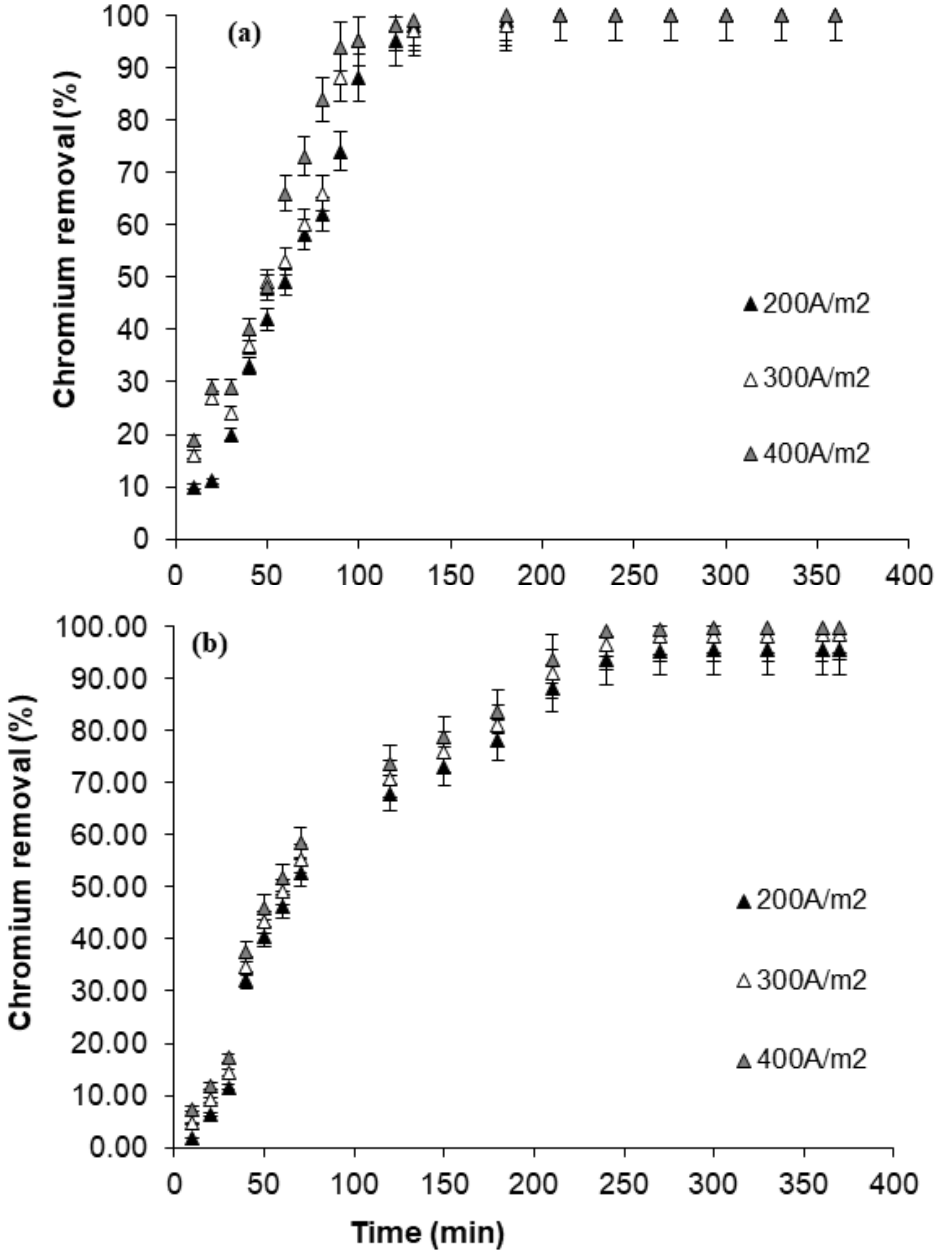


Figure 3. Effect of current density on chromium removal by EC process alone (a), and by EC combined to prickly pear cladode powder (EC/ PPP).

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These observations are consistent with those of several recent studies. For example, Meftah *et al.* (2023) highlight the growing interest in cactus-based powders for water and wastewater treatment. They emphasized the powders' biodegradability, low cost and ability to remove turbidity and suspended solids from water. Djerroud-Mohellebi *et al.* (2023) applied an electrocoagulation (EC) process assisted by the cladode mucilage of *Opuntia ficus-indica* to wastewater from a food additives production plant. Under optimal conditions — 200 mg L^{-1} mucilage, Al electrodes, a current density of 60 A m^2, an initial pH of 3 and a treatment time of 40 minutes — the COD removal efficiency reached 69.80 %. This demonstrates that combining EC with cactus-derived mucilage can significantly enhance the reduction of the organic load compared to conventional EC or chemical treatments, while potentially offering lower operational costs and energy consumption.

The results contrast with earlier studies on electrocoagulation alone (*e.g.,* Chen, 2004), which were effective but required longer treatment times and depended heavily on the applied current density to attain optimal removal levels. Coupling electrocoagulation with natural flocculants such as cactus cladode powder represents noteworthy progress, offering better effectiveness, reduced energy costs, and enhanced environmental sustainability in industrial effluent treatment processes.

Effect of prickly pear cladode powder concentrations

Figure 4 shows that the increase in the cladode powder concentration of the prickly pear in the electrocoagulation treatment process highly improves chromium removal efficiency. Chromium removal is slow in the absence of cactus flocculant (0 mg L^{-1}), reaching about 50.00 % of removal after 120 min. However, we observe gradual enhancement in chromium removal with increasing cactus powder concentrations. At the highest concentration of 20 mg L^{-1} chromium removal reaches nearly 100 % in less than 100 min (approximately 80 min). Thus, this demonstrates that cactus powder plays a crucial role in probably improving the coagulation and flocculation processes, consequently, this facilitates rapid elimination of chromium ions from water.

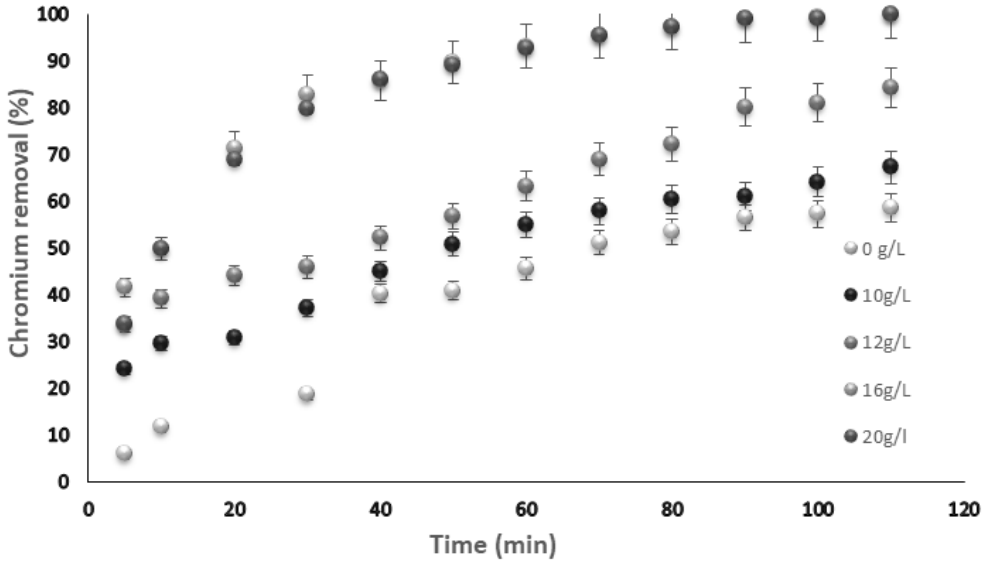


Figure 4. Effect of cactus powder concentration on removal efficiency (operating time 120 min, current density = 200 A m^2).

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These results are consistent with those of several other studies that have highlighted the effectiveness of natural coagulants in treating heavy metals. For example, Bouaouine *et al.* (2021) reported 96.00 % turbidity removal when using a cactus-derived coagulant in their study on textile wastewater, with significantly reduced sludge production compared with conventional chemical coagulants. Furthermore, Djerroud-Mohellebi *et al.* (2023) found that combining electrocoagulation (EC) with cladode mucilage of *Opuntia ficus-indica* achieved COD removal of ~70.00 % under optimal conditions. In our study, figure 4 shows that increasing prickly pear powder concentrations reduced the time required to achieve high removal rates. Other studies, such as that by Djerroud-Mohellebi *et al.* (2018), have also confirmed that natural coagulants made from plant extracts enhance depollution efficiency and reduce energy costs, thus improving the environmental sustainability of wastewater treatment processes. Electrocoagulation assisted by natural biopolymers such as cactus appears to be a promising solution due to the enhanced efficiency it provides and its low ecological impact, as demonstrated by previous studies. Thus, adding cactus powder to the electrocoagulation process not only allows for faster and more effective chromium removal, but also offers considerable environmental and economic advantages compared to traditional coagulants.

Effect of electrolysis time on treatment

The figure 5 shows the effect of time on the percentage of chromium removed using two methods: EC (electrocoagulation alone) and EC/PPP (electrocoagulation assisted by prickly pear cladode mucilage). Tests were conducted to compare the efficiency of the two processes in terms of the percentage of chromium removed over time. The results showed that the EC/PPP process achieved higher performance than EC alone, particularly in the early stages of treatment. After roughly 180–360 minutes, the highest chromium removal efficiencies are attained. Using the EC/PPP method, the removal percentage surpasses 90.00 % after 70 minutes, whereas using EC alone it reaches around 80.00 % after 180 minutes. Thus, the EC/PPP process demonstrated a faster capacity for chromium removal, achieving approximately 99.14 % in under 180 minutes, whereas EC alone barely exceeded 80.90 % within this timeframe.

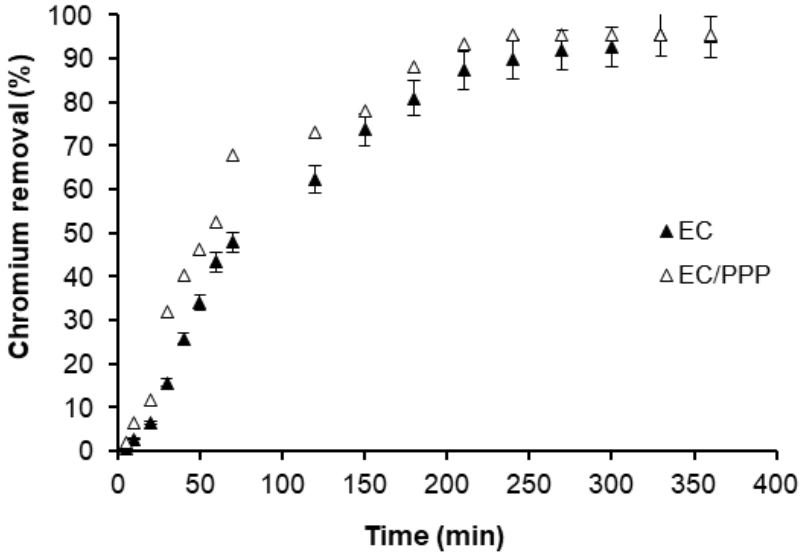


Figure 5. Contact time on percentage removal of prickly pear cladode powder concentration = 20 g L^{-1}, current density = 200 A m^2.

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These results may be related to the synergistic action of prickly pear cladode mucilage, which could enhance the flocculation process and improve chromium removal through precipitation or co-precipitation with aluminum hydroxides. These findings are consistent with those of other articles emphasizing the efficacy of electrocoagulation as a method of removing heavy metals. Merzouk *et al.* (2020) reported a removal efficiency of over 60.00 % at an optimum pH value of 7.8 using aluminum electrodes. Regarding the effect of pH on chromium removal efficiency, Vardhan *et al.* (2019) reported optimal results at pH values between 7 and 9, which is consistent with our findings. These results reaffirm the critical role of pH in EC processes and its impact on removal efficiency.

Fate of chromium and sludge management

Following electrocoagulation treatment, the chromium removed from the aqueous phase is likely to be transferred to the solid phase in the form of sludge generated through coagulation and precipitation processes. Sludge production is therefore an important parameter to consider when assessing the overall performance of the treatment process. In the present study, detailed characterization of the generated sludge, particularly in terms of its quantity and chromium content, was not performed. Therefore, these sludges should be considered as potentially contaminated residues and appropriately managed to prevent chromium remobilization or secondary environmental contamination. Physicochemical characterization and determination of the chromium concentration in the sludge would be necessary to assess its stability, potential for valorization or chromium recovery, as well as appropriate treatment and disposal conditions. Consequently, sludge management represents an important aspect that should be considered in a comprehensive environmental assessment of the EC/PPP process.

Figure 6 shows the energy consumption per kg of Cr(III) removed from chrome tanning wastewater treated by simple electrocoagulation and EC/AD coupling. For both treatments the energy consumption increased with an increase in the percentage of chromium removed. The prickly pear cladode powder addition decreases the electrical energy consumption by 50 – 70 % when compared with EC and its enhanced the treatment rate to reduce metal ion concentration below admissible legal levels. As can be seen in figure 6, there is a significant difference in energy consumption when comparing EC alone with EC combined with prickly pear cladode powder (EC/PPP).

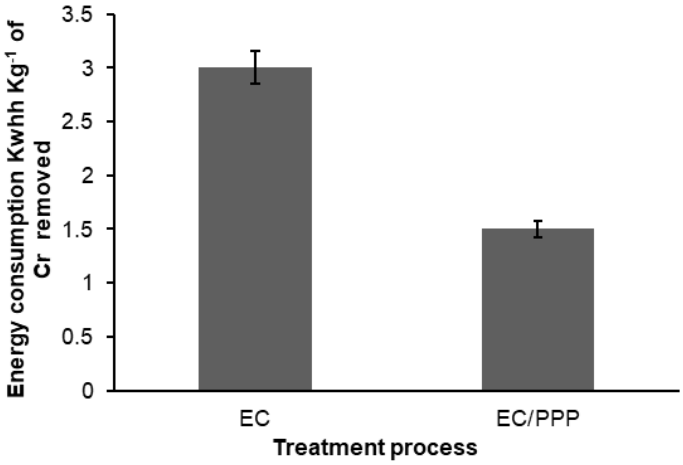


Figure 6. Specific energy consumption after treatment by EC/ PPP coupling process and EC alone.

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Energy consumption

The EC process consumed almost 3 kWh kg^{-1} of chromium, whereas the EC/PPP process consumed just 1.5 kWh kg^{-1} of chromium. The reduction in energy consumption by half when cactus powder is added could be explained by its positive effect on enhancing the flocculation of chromium or chromium complexed with various aluminum species ions released during the EC process. Consequently, this optimization reduces the time and energy required for chromium removal treatment.

Other recent studies have also highlighted the efficiency of natural coagulants in reducing energy costs in wastewater treatment processes (Remini and Madani, 2018). Remini and Madani (2018) demonstrated that incorporating cactus mucilage into the electrocoagulation-electroflotation process resulted in reduced energy costs compared to conventional electrocoagulation (EC). They attributed this reduction to the biopolymers' ability to accelerate floc formation.

Similarly, several studies have reported that adding natural coagulants to electrocoagulation can improve performance by reducing energy demand and the amount of coagulant needed to achieve high removal efficiencies for heavy metals such as chromium. For example, using chitosan, a plant-based coagulant, has been shown to improve metal removal in wastewater treatment, minimize chemical usage, and increase the sustainability of the process (Rockson-Itiveh *et al.*, 2024). Adding prickly pear cladode powder to the EC process significantly reduces energy consumption while maintaining effective treatment performance. These findings emphasize the economic and ecological advantages of utilizing natural flocculants in water treatment.

Conclusions

This study evaluated the effect of adding prickly pear cladode powder to the electrocoagulation (EC) treatment process to enhance its efficiency. The promising results show that the current density applied during EC treatments plays a decisive role in determining the performance of the process. This directly influences the rate of coagulant generation and affects the size and distribution of gas bubbles, both of which are essential for effective floc formation and, consequently, the removal of chromium pollutants. This study investigated current density values of 200, 300 and 400 A m^2 over treatment times ranging from 5 to 360 minutes, both in EC alone and in a combined EC/prickly pear cladode powder (EC/PPP) treatment. Increasing the current density generally led to improved chromium removal efficiency by accelerating the EC reactions and thereby enhancing the coagulation process. However, the advantages must be balanced against the increased energy demand and potential operational constraints at higher intensities. Furthermore, integrating prickly pear powder into the EC process enhanced the treatment performance, particularly by improving floc formation stability and promoting favorable pH progression over time.

Overall, the findings confirm that optimizing current density is crucial to maximizing the effectiveness of the EC process and that adding the bio-flocculant offers a sustainable, efficient, green solution for depolluting chromium-containing wastewater.

The results of this study suggest that the EC/PPP process could reduce the demand for electrical energy while promoting the utilization of cactus biomass as a treatment aid. Integrating cactus biomass with electrocoagulation improves treatment performance and reduces specific energy consumption compared to EC alone. These findings suggest an environmental benefit to the combined process.

However, a comprehensive environmental assessment is required to confirm its overall environmental performance, including aspects such as sludge management, residual aluminum, biomass production and life-cycle impacts. Such an assessment will be considered in future work.

An important perspective of this study concerns the fate of chromium following EC/PPP treatment. Since the chromium removed from the aqueous phase is likely to be transferred to the sludge generated during the treatment process, further characterization of this sludge is needed. Future studies should determine the amount of sludge produced, its chromium content, stability, and potential for valorization or chromium recovery. Appropriate sludge management and disposal should also be investigated in accordance with the applicable regulatory requirements for waste containing heavy metals. These additional investigations will provide a more comprehensive assessment of the overall environmental performance and sustainability of the EC/PPP process.

ETHICS STATEMENT

Not applicable.

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF SUPPORTING DATA

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

COMPETING INTERESTS

The authors declare that they have no competing interests.

FUNDING

Not applicable.

AUTHOR CONTRIBUTIONS

Conceptualization, S.E. and N.A.; Methodology, S.E. and J-P., L., Software, S.E.; Validation, S.E., N.A.; Formal analysis, S.E.; Investigation, S.E.; Resources, J-P.L ., L.M and N.O.; Data curation, S.E.; Writing—Original draft preparation, S.E.; Writing—Review and editing, S.E and L. Mi.; Visualization, S.E and N.A .; Supervision, S.E.; Project administration, N.O.; Funding acquisition, N.O.

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