Chemical Papers (2026) 80:6491–6500
https://doi.org/10.1007/s11696-026-04780-y

ORIGINAL PAPER

Degradation/mineralization of carwash wastewater by coupled process electrocoagulation/electro-Fenton

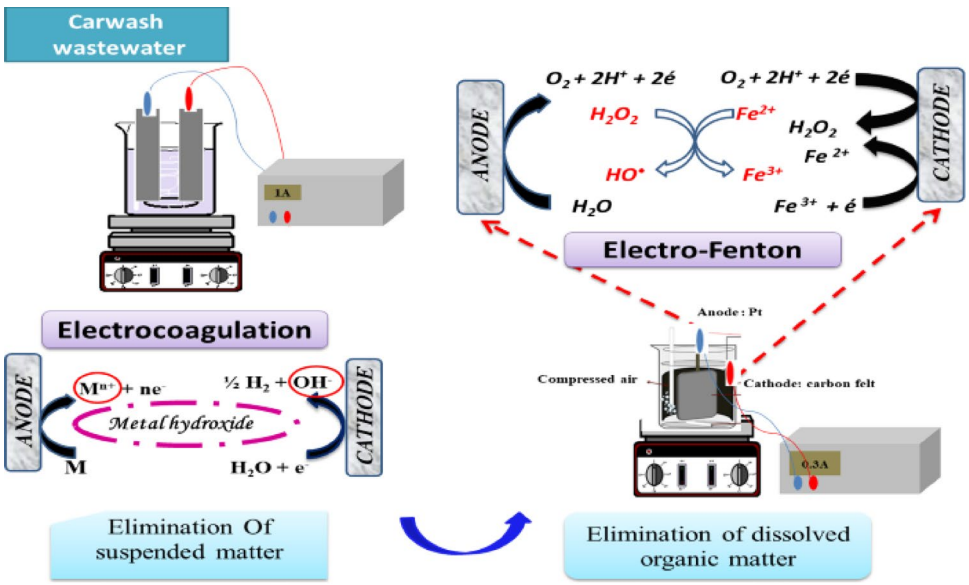
Najwa Hamdi[1] · Ibtissem Boumnijel[2] · Mabrouk Mosbahi[3,4,5] · Khaled Gammoudi[4,5] · Ibrahim Mabrouki[5] · Baghdadi Aloui[6] et al. ***[full author details at the end of the article]***

Received: 7 November 2025 / Accepted: 3 March 2026 / Published online: 23 March 2026

Abstract

The importance of this work lies in the application of a combined electrocoagulation/electro-Fenton (EC/EF) treatment for carwash wastewater, offering a cost-effective and efficient remediation approach. During electro-coagulation (EC), experiments were carried out in a cylindrical cell containing 450 mL of carwash wastewater. This process promotes the formation of $Fe(OH)_n$ (n=2 or 3) as coagulants, along with Fe^{3+}/Fe^{2+} ions acting as catalysts. The effects of key operating parameters, including applied current, electrode material (Fe and Al), and initial pH, were evaluated, and both COD removal and energy consumption were assessed. In the EF stage, comparative trials were performed in stirred reactors equipped with a Pt anode and a carbon-felt cathode under O_2 bubbling to generate H_2O_2 at the cathode. The hydroxyl radicals produced at the anode surface through water oxidation and in the bulk solution via Fenton's reagent (Fe^{2+}/H_2O_2) promote the oxidative degradation of organic contaminants. The effects of the supporting electrolyte, applied current and the catalytic activity were investigated to optimize electro-Fenton efficiency. Under optimal EC conditions (I=1 A, Fe electrode, pH=5.7), 76.58% COD removal was achieved with an energy consumption of 0.987 kWh·m^{-3}. Nearly complete COD removal (97.8%) was obtained using the combined process, where residual organics after EC were removed during electro-Fenton treatment at 0.3 A for 360 min.

Graphical abstract



Keywords Wastewater treatment · Carwash wastewater · Electrocoagulation · Electro-Fenton · Chemical oxygen demand

Introduction

Water recycling offers an important opportunity to address increasing water demands driven by population growth and expanding agricultural and industrial activities. Carwash operations consume large volumes of water and generate effluents containing a wide range of pollutants. Carwash wastewater discharge in Tunisia is not specifically documented in national reports, but such effluents fall under the country's general wastewater regulations, which require proper treatment before release into the environment. In practice, large commercial carwash facilities are usually connected to the municipal sewer network operated by ONAS, often with basic pre-treatment steps such as oil and sediment separation, while some installations incorporate on-site recycling systems to reduce discharge volumes. However, smaller or informal carwash operations may lack adequate infrastructure and can discharge untreated wastewater into storm drains or onto surrounding soils. These practices occur within a broader context of national challenges in wastewater management, where insufficient treatment and unregulated discharges contribute to environmental pollution. Globally, water consumption in the carwash sector is significant: washing a car in a commercial facility requires about 150 L of water (Tamiazzo et al. 2015), while washing trucks or buses uses 400–600 L (Almeida et al. 2010). An empirical study in São Paulo estimated that the industry consumes more than 1.3 million gallons of freshwater per day (Almeida et al. 2010). Nevertheless, in Kuwait, daily usage is reported to be roughly twice as high (Al-Odwani et al. 2007). Worse still, carwash wastewater typically contains contaminants such as oils and grease, detergents and surfactants, degreasers, volatile organic and sulfur compounds, various nitrogen- and phosphorus-based species, plasticizers, brake dust from rubber linings, and several heavy metals (Kiran et al. 2015, Boluarte et al 2016. Several processes such as chemical oxidation (Bhatti et al. 2011), membrane separation (Boussu et al. 2007; Lau et al. 2013; Kiran et al. 2015), and electrocoagulation (EC) (Afshin et al. 2011) have been reported to be useful in treating carwash wastewater. Electrocoagulation (EC) is a conventional physico-chemical treatment based on the in situ release of metallic cations through the dissolution of sacrificial anodes. These cations act as active coagulant precursors, as their hydrolysis leads to the formation of insoluble polymeric metal hydroxides. Iron and aluminum are the most commonly used electrode materials due to their low cost and the high valence of their ionic species. The main reactions involved in the formation of these metal hydroxides are summarized in the following reactions (Thiam et al. 2014). At the cathode, the predominant reaction is hydrogen evolution (Panizza and Cerizola, 2010).

$$Al_{(s)} \rightarrow Al^{3+}_{(aq)} + 3e^{-} \quad \text{(R. 1)}$$

$$Fe_{(s)} \rightarrow Fe^{2+}_{(aq)} + 2e^{-} \quad \text{(R. 2)}$$

$$Al^{3+}_{(aq)} + 3H_2O \rightarrow Al\,(OH)_{3(s)} + 3H^{+}_{(aq)} \quad \text{(R. 3)}$$

$$4\,Fe^{2+}_{(aq)} + 10\,H_2O + O_{2(g)} \rightarrow 4\,Fe\,(OH)_{3(s)} + 8\,H^{+}_{(aq)} \quad \text{(R. 4)}$$

$$2\ H_2O\ + 2\ e^{-} \rightarrow H_2 + \ 2\ OH^{-} \quad \text{(R. 5)}$$

Among recent advanced treatment technologies, the electro-Fenton (EF) process has gained significant attention due to its effectiveness in treating various real industrial effluents, including slaughterhouse wastewater (Paramo-Vargas et al., 2015), textile dyeing effluents (Ghambari et Moradi, 2015), and winery wastewater (Díez et al. 2017). In the EF process, highly reactive hydroxyl radicals are generated through the combination of Fenton's reaction (R.6) and electrochemical mechanisms. The Fenton reagents, H_2O_2 and Fe^{2+}, are continuously produced and regenerated, respectively. Specifically, H_2O_2 is formed in situ by the two-electron reduction of oxygen at the cathode (R.7). At the same time, ferrous ions are regenerated through the electrochemical reduction of ferric ions at the cathode (R. 8).

$$Fe^{2+} + H_2O_2 \rightarrow Fe^{3+} + {}^{\bullet}OH + OH^{-} \quad \text{(R. 6)}$$

$$O_2 + 2\ H^{+} + 2\ e^{-} \rightarrow H_2O_2 \quad \text{(R. 7)}$$

$$Fe^{3+} + e^{-} \rightarrow Fe^{2+} \quad \text{(R. 8)}$$

Electrochemical treatments have been applied to a wide range of wastewater types, including textile effluents (Khouni et al. 2020; Agarwal et al. 2024), dye-manufacturing wastewater (Ustun 2021), mixed industrial effluents and synthetic systems designed to target specific micropollutants such as tetracycline (Zhou et al. 2024). While these studies highlight the strong potential of EC–EF systems, recent reviews (García-Segura and Brillas, 2017) underline persistent challenges, including high energy demand, pH sensitivity, limited sludge/iron optimization, and the need to extend applications to more complex real wastewater matrices. Moreover, EC or EF processes applied individually to carwash, oily, or industrial wastewaters typically require longer treatment times and/or higher energy input to reach high COD removal efficiencies (Mousazadeh et al. 2024) To overcome the limitations of these researches performed based on single-step treatments, this study is the first to investigate a two-step electrochemical treatment, electrocoagulation (EC) followed by electro-Fenton (EF), for real carwash effluent. To the best of our knowledge, no

Table 1 Carwash wastewater characteristics

Parameter	value
COD (mg O_2/L)	800
pH	5,7
Suspended matter (g/L)	2,65
Dry matter (g/L)	26
Dry matter (g/L)	26
Conductivity (mS/cm)	4,2
Phosphate (mg/L)	6,8–9,5

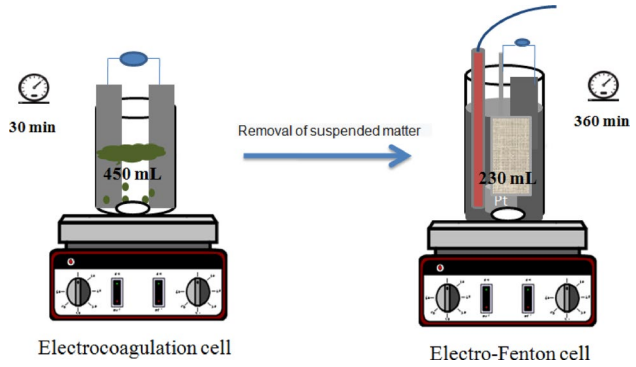


Fig. 1 Schematic representation of the combined EC/EF treatment

previous work has focused on carwash wastewater, which contains a unique and under-studied mixture of oils, surfactants, detergents, suspended solids, and hydrocarbons. Here, a purposefully optimized sequential EC/EF process is applied, with systematic evaluation of electrode material, current density, pH, electrolyte effects, and catalytic performance to develop an energy-efficient treatment for this complex wastewater. In this approach, EC serves a dual role as both an effective pre-treatment and a catalyst source, generating $Fe(OH)_n$ (n=2 or 3) coagulants and releasing $Fe3^{+}/Fe2^{+}$ ions (Thiam et al. 2014). Overall, the aim is to enhance coagulation of the high organic load during EC pre-treatment and achieve near-complete mineralization during EF post-treatment, while minimizing energy consumption. The influence of key operating parameters on COD removal and energy demand was examined in detail.

Materials and methods

Sample collection

The wastewater used in this study was collected from a carwash station located in Gabes (Tunisia), and its characteristics are presented in Table 1.

Electrochemical treatment

The two-step electrochemical treatment is illustrated in Fig. 1.

Electro-coagulation cell

The electro coagulation cell consisted of a cylindrical Pyrex reactor containing 450 mL of carwash wastewater. The electrode pair, made of either iron or aluminum, consisted of plates with dimensions of 10 cm × 5 cm × 0.25 cm and an immersed length of 6 cm. The electrodes were positioned in parallel with an inter-electrode distance of 4 cm and connected to a power supply. Electrolysis was performed using the natural conductivity and pH of the wastewater, without any supporting electrolyte (Labiadh et al. 2016), at room temperature and under constant applied currents ranging from 0.2 to 2 A (Fig. 1).

Electro-Fenton cell

At the end of electro-coagulation, the solution was centrifuged for 30 min at 5000 rpm to remove the precipitate, and 230 mL of the resulting supernatant was transferred to an electrolytic cell stirred with a magnetic bar. The anode consisted of a cylindrical platinum (Pt) electrode, surrounded by a carbon felt piece (12 cm × 4 cm × 0.5 cm) lining the internal wall of the cell, which served as the cathode. Before electrolysis, the pH of the solution was adjusted to 3 using H_2SO_4 (Scharlau Chemie S.A.), and the solution was bubbled with compressed air for approximately 10 min to achieve oxygen saturation for in situ H_2O_2 generation at the cathode. $FeSO_4$ was added as a catalyst at a concentration of 0.1 mM (Fig. 1).

Each electrolysis was repeated at least twice, with differences in COD values below 5% in most cases.

Analytical methods

Conductivity and pH were measured using a C830 multiparameter analyzer. Throughout the experiments, samples were periodically collected and analyzed. Chemical oxygen demand (COD) was determined using a Shimadzu 1650 UV–Vis spectrophotometer at $\lambda = 600$ nm.

The specific energy consumption per unit volume (E_C in $KWh.m^{-3}$) was calculated using Eq. 1.

$$E_c = \frac{U \times I \times t}{3600 \times V} \quad (1)$$

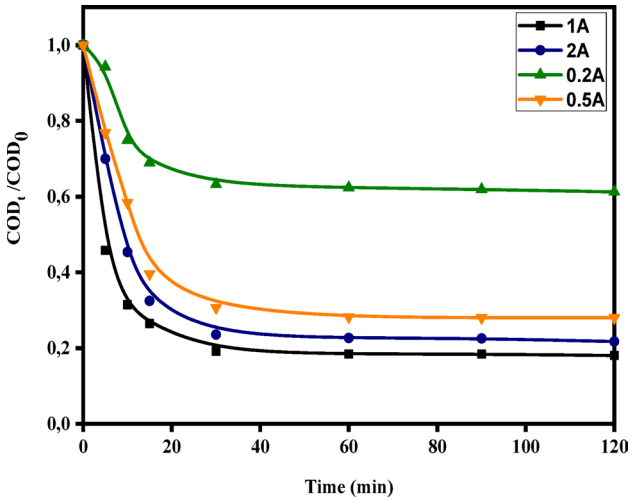


Fig. 2 Effect of applied current on COD abatement during the EC of carwash wastewater using Iron Electrodes

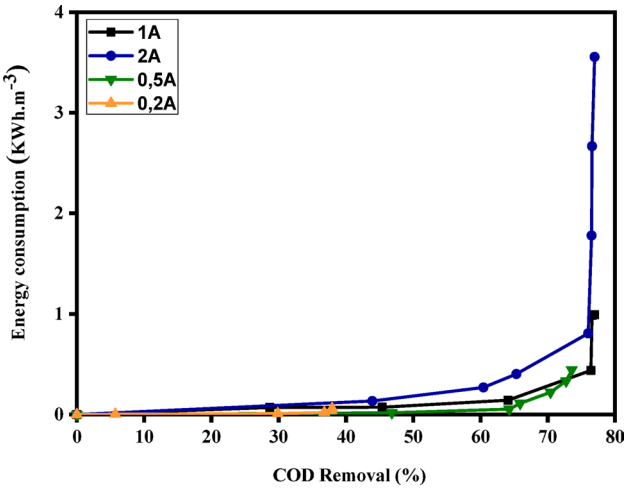


Fig. 3 Evolution of the specific energy consumption versus COD degradation during the EC of carwash wastewater using Iron Electrodes at different applied current

where U is the average cell voltage (V), I the current (A), t the electrolysis time (s) and V the volume of the treated solution (dm^3).

The COD abatement rate was computed based on Eq. 2.

$$\%COD = \frac{COD_0 - COD_t}{COD_0} \times 100 \quad (2)$$

where COD_0 and COD_t are the experimental values at initial time and time t, respectively.

The concentration of Fe^{2+} was determined using the spectrophotometric method with 1,10-phenanthroline, which forms a stable orange–red complex with Fe^{2+}. The absorbance was measured at $\lambda = 510$ nm and the Fe^{2+} concentration is determined from a calibration curve.

Results and discussion

Carwash wastewater treatment by Electro-coagulation

The applied current is a key parameter in the electro-coagulation process, as it regulates the generation of reactive species responsible for oxidizing persistent organic matter in the solution. Currents between 0.2 and 2 A were applied to investigate this effect by electrolyzing 450 mL of carwash wastewater using Fe/Fe as the anode/cathode pair, without added supporting electrolyte, at the natural pH of 5.7. The pH was continuously monitored because OH^- ions generated at the cathode could be partially neutralized by H^+ formed during R.4, resulting in a tendency for pH to increase (Thiam et al. 2014). The obtained results are illustrated in Fig. 2. As seen in this Figure, the enhanced COD removal with increasing applied current can be attributed to the Fe dissolution rate and the formation of iron hydroxides $Fe(OH)^{2+}$, $Fe(OH)_2^+$, $Fe(OH)_3$, $Fe(OH)_4^-$, which are rapidly removed from the solution as amorphous precipitates (Isarain-Chavez et al., 2014). However, further increasing the current from 1 to 2 A leads to high energy consumption without significantly improving COD removal, resulting primarily in excessive iron anode dissolution.

Figure 3 illustrates the evolution of energy consumption at different applied currents during electro-coagulation of the effluent. In all cases, energy consumption increases with current linearly at low COD removal and exponentially at high COD removal. This trend can be explained by the successive formation of reaction products, which increases energy demand. It also indicates that oxidation occurs at current intensities higher than the minimum required to oxidize the effluent's organic content (Panizza et al., 2010). Considering both COD removal efficiency and energy consumption, an applied current of 1 A is sufficient to effectively reduce the wastewater COD.

Some studies have shown that the differing performance of iron and aluminum anodes in wastewater treatment can be attributed to their varying abilities to enhance charge neutralization (Thiam et al. 2014). The COD removal profiles obtained during EC trials are shown in Fig. 4.

Figure 4.a shows that COD removal is consistently higher with iron electrodes than with aluminum under the same experimental conditions. This can be explained by the dissolution of Fe^{2+} ions, which promotes coagulation through the formation of iron hydroxides, facilitating flocculation and trapping of organic matter. In contrast, COD removal with aluminum anodes reached only 45.8%, compared to 76.58% with iron, due to the lower adsorption capacity

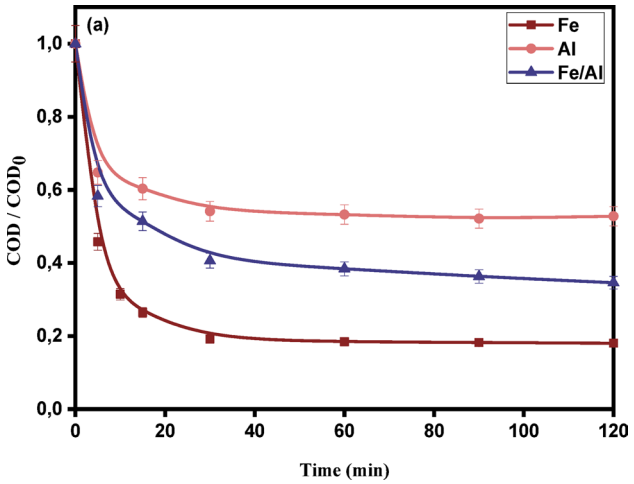


Fig. 4 **a** Effect of electrodes on COD degradation by EC during carwash wastewater treatment (I = 1A). **b** Energy consumption versus COD degradation by EC during carwash wastewater treatment (I = 1A)

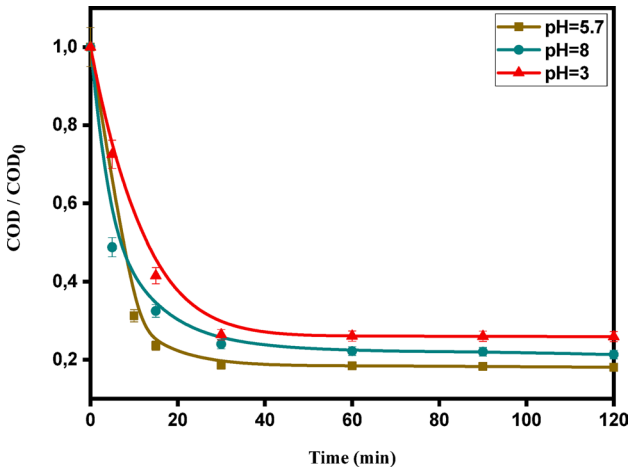


Fig. 5 Effect of pH on COD degradation by EC during carwash wastewater treatment at different pH values (I = 1A, Electrodes: Fe/Fe)

of $Fe(OH)_3$. Additionally, carwash wastewater contains agents that inhibit aluminum surfaces, slowing coagulation of colloidal matter and reducing therefore electro-coagulation efficiency. As seen in Fig. 4.b, energy consumption increases linearly at low COD removal but rises sharply at higher abatement levels. For instance, achieving 76.58% COD removal with iron electrodes required 0.987 $kWh \cdot m^{-3}$, whereas aluminum electrodes consumed 0.92 $kWh \cdot m^{-3}$ to reach only 45.8% COD removal under the same conditions. These results indicate that using iron electrodes as sacrificial anodes provides high COD removal efficiency with relatively low energy consumption, not only due to superior coagulation performance but also because of their potential catalytic properties in subsequent coupling with Electro-Fenton processes.

It is well known that the EC process depends on the solution pH, due to the wide range of equilibria involved (Thiam et al. 2014) and their importance in the formation of iron hydroxides. Accordingly, its effect was investigated over a pH of 3–8.

In real carwash effluents, pH-dependent iron transformations interact with additional matrix factors, such as colloidal stability, surfactant chemistry, and ionic strength, which collectively influence the efficiency of EC. Anionic surfactants and detergent-derived micelles stabilize oily colloids and dispersed solids, often shielding organic matter from direct electrochemical oxidation (Khan et al. 2015). During the EC process, as shown in Fig. 5, the COD removal is slower and less significant at pH 3 (Fernandes et al. 2014). Near neutral pH (pH ≈ 5.7), the formation of iron-based flocs (e.g., $Fe(OH)_2$ and $Fe(OH)_3$) more effectively destabilizes these colloidal structures, thereby enhancing coagulation and co-adsorption processes (Mollah et al. 2004). Similarly, the relatively high ionic strength characteristic of carwash wastewater compresses the electrical double layer, promoting particle aggregation and improving floc–pollutant interactions (Gregory 2006). These synergistic effects help explain why operation at natural pH conditions (pH = 5.7) results in the most rapid and pronounced COD reduction. At pH 8, iron solubility increases due to the formation of soluble hydroxo-complexes (e.g., $Fe(OH)_4^-$), leading to a reduced COD removal rate (Cheng et al. 2016). At even higher alkaline pH values, COD abatement becomes slower, likely owing to diminished formation of amorphous iron precipitates. To optimize both treatment efficiency and operational cost, subsequent EC experiments will therefore be conducted at an initial pH of 5.7. Under these conditions, favorable Fe(II)/Fe(III) cycling, robust floc formation, and enhanced destabilization of surfactant-stabilized colloids are achieved, ultimately improving COD removal.

Carwash wastewater treatment by the combined EC/EF process

After 30 min of EC treatment, 76.58% COD removal was achieved, beyond which no significant further reduction was observed, underscoring the need for EF post-treatment. Accordingly, the combined EC/EF process was performed. Figure 6 shows the COD abatement trends observed after the combined EC/EF treatment of carwash wastewater. Actually, the solution was first pretreated by EC (Fe/Fe, 30 min, 1A, pH 5.7).The samples were then centrifuged, and the residue was treated by EF at pH 3, chosen as the optimal value for the process (Sun and Pignatello 1993; Sirés and Brillas 2017), using carbon felt as the cathode and platinum as the anode. Prior to EF application, the total iron concentration was measured to be 0.9 mM, which falls within the optimal range (≈0.1–1 mM) for effective EF treatment (Brialls et al.,

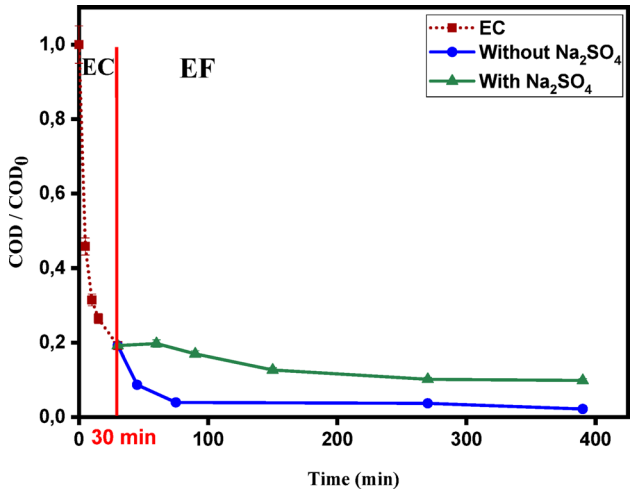


Fig. 6 Influence of supporting electrolyte on COD degradation during the EF step of the combined EC (Fe/Fe, 30 min, 1A, pH 5,7) / EF (Pt / carbon-felt, 0.3A, pH 3.0) process

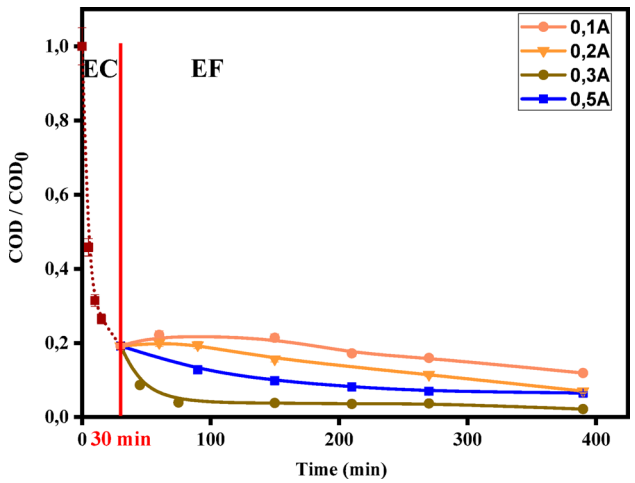


Fig. 7 Effect of applied current density on COD degradation during the EF step of the combined EC (Fe/Fe, 30 min, 1A, pH 5,7) / EF (Pt / carbon-felt, pH 3.0) process

2009). As shown in Fig. 6, the sequential EC–EF treatment of carwash wastewater promotes rapid COD removal.

During the second step of the combined EC/EF process, the effects of several operating parameters, namely the presence of a supporting electrolyte, the use of a catalyst, and the applied current density, on COD removal from carwash wastewater were investigated.

According to the literature review, sodium sulfate (Na_2SO_4) is a preferred supporting electrolyte for EF due to its low cost and environmental compatibility. To evaluate its effect on carwash wastewater treatment, two experiments were conducted during the EF process, with and without Na_2SO_4. As shown in Fig. 6, the presence of Na_2SO_4 has a negligible effect, likely because sulfate ions promote secondary reactions such as persulfate formation (R.9) (Clematis et al. 2016). These results suggest that the inorganic ions naturally present in the effluent provide sufficient conductivity to reduce ohmic potential and govern the oxidation rate.

$$2SO_4^{2-} \rightarrow S_2O_8^{2-} + 2H^+ + 2e^- \quad \text{(R. 9)}$$

The applied current is a key parameter governing both the efficiency and the operational cost of Electrochemical Advanced Oxidation Processes (EAOPs). It directly affects the formation of hydroxyl radicals (Brillas et al. 2009; Barhoumi et al 2016; and Ammar et al. 2015), the regeneration rate of Fe^{2+}, and thus the overall oxidation capacity of the EF system. The influence of current density was evaluated at 0.1, 0.2, 0.3, and 0.5 A. As shown in Fig. 7, the highest COD removal rate was obtained at 0.3 A, where the excess charge in the electrochemical cell promotes the electrogeneration of hydroxyl radicals, achieving 97.8% COD removal after 360 min (6 h) of treatment. It should also be noted that increasing the current from 0.3 A to 0.5 A leads to a progressive enhancement of parasitic reactions, such as water formation from hydrogen evolution (R.10 and R.11), which consumes electrons and reduces the production of hydroxyl radicals. Consequently, the process efficiency decreases at higher current intensities. Increasing the current intensity above 0.3 A does not lead to a further improvement in COD removal but instead causes an excessive dissolution of the iron electrode (Panizza and Cerisola 2010). Therefore, considering the removal efficiency and electrode stability, 0.3 A is selected as the optimal current density for the EF process.

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad \text{(R. 10)}$$

$$2H^+ + 2e^- \rightarrow H_2 \quad \text{(R. 11)}$$

The final parameter investigated in the EF process was the presence of a catalyst and its impact on COD degradation in carwash wastewater. In EF systems, the catalyst is essential for activating the Fenton reaction. Accordingly, two experiments were conducted, with and without the addition of ferrous sulfate ($FeSO_4, 7H_2O$), at pH 3.0, previously reported as optimal for EF operation.

As shown in Fig. 8, adding an external catalyst does not significantly improve treatment performance compared to the catalyst-free condition, despite the exponential COD decrease observed in both cases. This behaviour is primarily governed by the iron concentration in the system. During EC pre-treatment, approximately 0.9 mM of Fe^{2+} is released within the first 30 min, enabling COD removal to reach 76.58%. In contrast, the external addition of Fe^{2+} (as $FeSO_4, 7H_2O$) introduces an excess of free Fe^{2+}. Although Fe^{2+} is essential for the Fenton reaction,

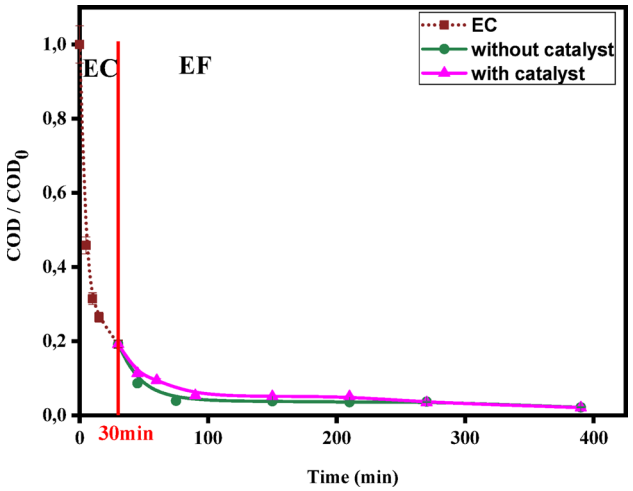


Fig. 8 Effect of the catalyst ($FeSO4,7H_2O$) on COD degradation during the EF step of the combined EC (Fe/Fe, 30 min, 1A, pH 5.7) / EF (Pt / carbon-felt, 0.3A, pH 3.0) process

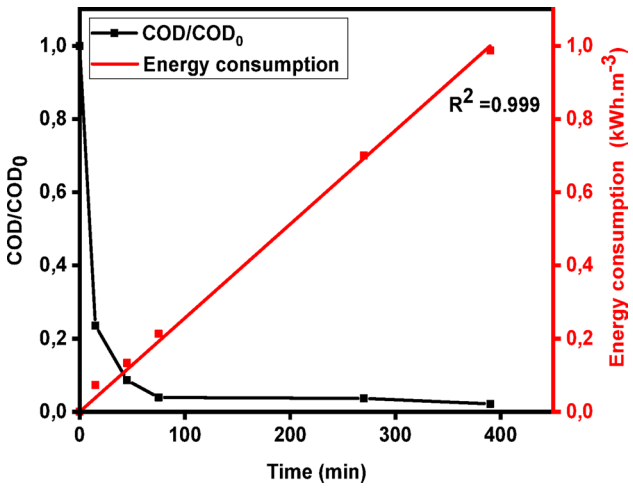


Fig. 9 Evolution of COD degradation and energy consumption during the combined EC (Fe/Fe, 30 min, 1A, natural pH 5.7) / EF (Pt / carbon-felt, 0.3A, pH 3.0) process

reacting with H_2O_2 to generate hydroxyl radicals (•OH) (R.6), an excess of Fe^{2+} promotes the scavenging of •OH (R.12), thereby reducing their availability for pollutant oxidation (R.13) and leading to lower mineralization efficiency (Loaiza-Ambuludi et al. 2013). Moreover, an imbalance in the Fe^{2+}/Fe^{3+} redox cycle hinders the regeneration of Fe^{2+} from Fe^{3+} (R.8), leading to Fe^{3+} accumulation and the potential formation of inert precipitates, which further slows the catalytic cycle. These combined effects inhibit the EF oxidation pathway at high Fe^{2+} concentrations. This explanation, supported by literature, highlights the importance of optimizing iron dosage to maintain efficient radical production and sustainable iron cycling. Consequently, elevated free-Fe^{2+} levels can suppress both Fenton reactivity and H_2O_2 decomposition. The results demonstrate that Fe^{2+} generated in situ during EC enhances EF oxidation more efficiently (Isarain-Chavez et al., 2014). Therefore, considering both treatment performance and operational cost, performing EF without external catalyst addition is the preferred approach for carwash wastewater treatment.

$$\text{Excess } Fe^{2+} + {}^{\bullet}OH \rightarrow Fe^{3+} + OH^{-} \quad \text{(R. 12)}$$

$$\text{Pollutants} + {}^{\bullet}OH \rightarrow CO_2 + H_2O \quad \text{(R. 13)}$$

Figure 9 illustrates the evolution of COD removal and energy consumption during the sequential EC–EF treatment of carwash wastewater under optimal conditions. The EC pretreatment promotes the coagulation of a large fraction of organic matter, which can be efficiently removed by electrocoagulation (Panizza and Cerisola 2010). In addition, EC releases dissolved iron species that act as catalysts, enabling subsequent mineralization during the EF step. A marked decrease in COD is observed during the initial stage of electrolysis, reaching 76.58% after 30 min, which can be attributed to the effective removal of surfactants, oils, and greases through their entrapment in the formed flocs. In contrast, dissolved organic matter remains in solution and is subsequently degraded during the EF process. Energy consumption increases almost linearly with time ($R^2 = 0.999$). Under these conditions, the sequential EC/EF process achieves higher COD removal with lower energy consumption after 6 h of treatment. This performance compares favorably with similar studies reported in the literature, where electrocoagulation or electro-Fenton processes applied individually to carwash, oily, or industrial wastewaters typically require longer treatment times and/or higher energy input to reach comparable COD removal efficiencies (Panizza and Cerisola 2010; Brillas et al. 2009; Ghanbari and Moradi 2015). The improved energy efficiency observed in the present study can be attributed to the effective removal of hydrophobic and colloidal organic matter during the EC pretreatment, followed by enhanced mineralization during the EF step, thereby reducing the overall energy demand of the process.

The EC process actes as an effective coagulation step, initiating the decolorization of the solution. Oxidation by hydroxyl radicals generated from Fenton's reaction in the presence of H_2O_2 further accelerates color removal (Garcia-Segura et al. 2012; Moreira et al. 2013). Sequential treatment demonstrated the capability to gradually mineralize organic compounds into inorganic ions and CO_2, achieving up to 84.15% color removal, calculated as follows:

$$Color\ removal\ (\%) = \frac{A_0 - A_t}{A_0} \times 100 \quad (3)$$

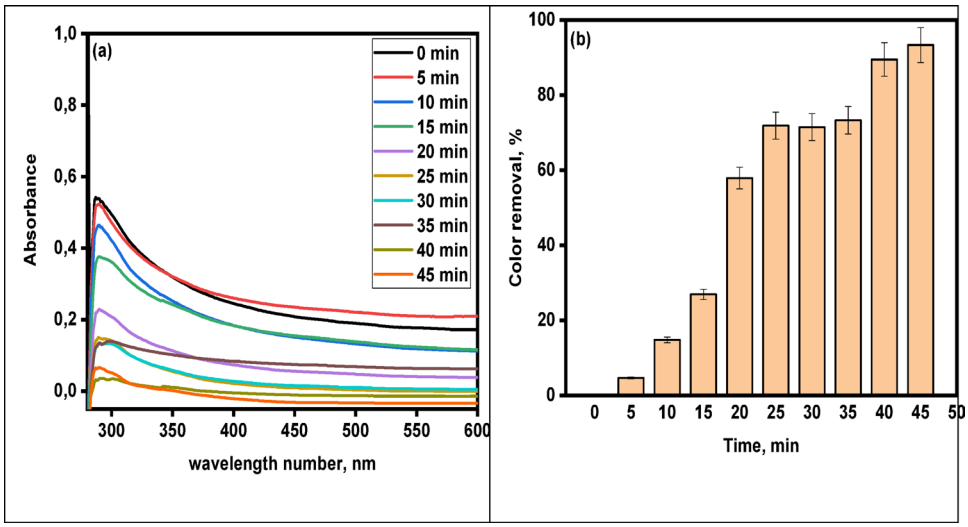


Fig. 10 **a** UV–Vis spectra change during the carwash wastewater electrolysis time. **b** Color removal as a percentage versus electrolysis time

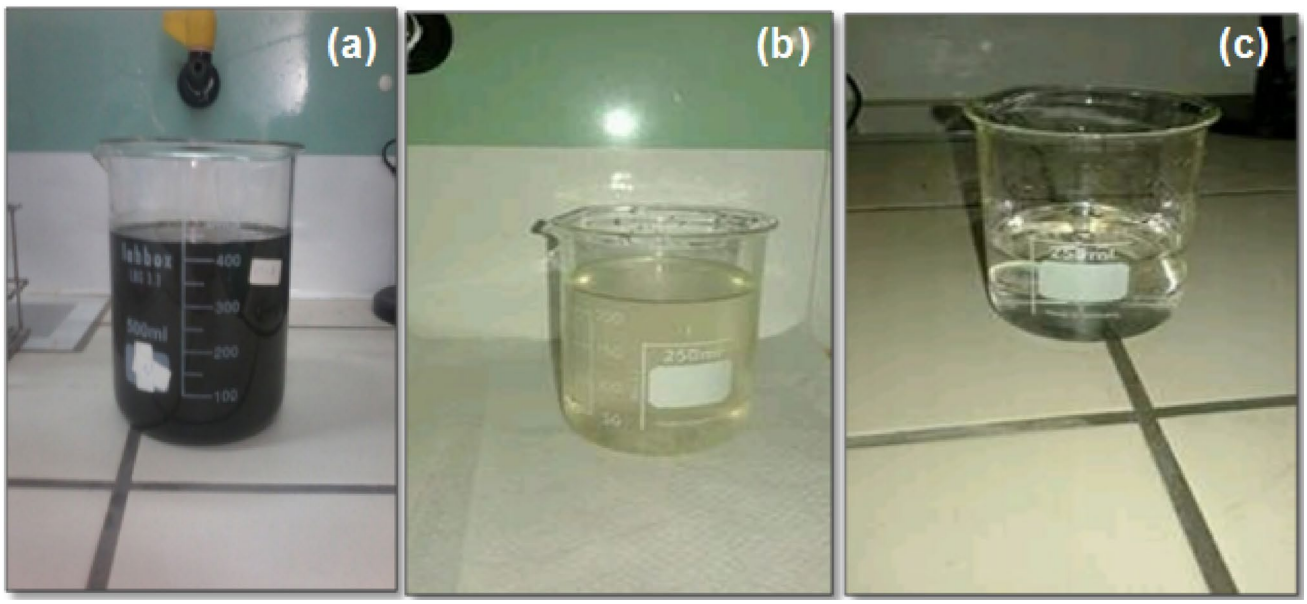


Fig. 11 Visual comparison showing the extent of color removal during the combined EC/EF treatment: **a** raw carwash wastewater, **b** after EC pretreatment, and **c** after EF mineralization

where A_0 and A_t are the absorbance values at the initial time and at time t, respectively. UV–Vis spectra, illustrated in Fig. 10, show a gradual decrease in the absorbance band at 289 nm where the initially colored solution becomes nearly colorless after 45 min of treatment, confirming the efficiency of the combined EC/EF process (Fig. 11). Although significant color removal and COD reduction are achieved within the first 45 min of electrolysis, the treatment in this section was extended to 360 min for several reasons. First, reaching a plateau in color or COD at 45 min does not necessarily indicate complete degradation of all oxidizable species. Electrochemical processes, particularly those involving indirect oxidation pathways (HO•, H_2O_2, Fe^{2+}/Fe^{3+}, etc.), can continue to degrade intermediate organic compounds long after visible color disappearance. Second, long-duration electrolysis allowed evaluation of kinetic behavior, mineralization efficiency, intermediate formation and degradation, and electrode stability over extended operation, parameters that short-term experiments cannot capture. Additionally, maintaining electrolysis up to 360 min provided essential information on energy consumption ($kWh \cdot m^{-3}$), specific removal rates, and operational reliability, which are critical for process optimization, scale-up, and cost–benefit analysis. Finally, extended operation verified that no secondary pollution, such as accumulation of partially oxidized intermediates or release of metal ions, occurred. For these reasons, although treatment objectives appeared to be met after 45 min, continuing electrolysis to 360 min was necessary

to fully characterize the process, confirm its stability, and determine the optimal operating parameters.

Conclusion

The sequential EC–EF treatment of carwash wastewater promoted rapid COD removal. EC removed a large fraction of organic matter through coagulation with iron hydroxides, while EF degraded dissolved organics via oxidation by hydroxyl radicals. During EC pre-treatment, the degradation process was strongly influenced by key operating parameters, including applied current, solution pH, and electrode type. Under optimal EC conditions (1 A, iron anode, pH 5.7), a COD removal of 76.6% was achieved after 30 min. Subsequent EF treatment over 6 h using a Pt/carbon felt cell at 0.3 A and pH 3.0 further increased COD removal to 97.8%, converting organics into CO_2 and H_2O. The proposed combined approach overcomes the limitations of individual processes, reduces energy consumption, and provides a practical solution for large-scale carwash wastewater treatment, contributing to environmental protection.

Acknowledgements The author gratefully acknowledges the University of Palermo for the financial support provided, which made this work possible.

Author contributions H.N. and A.B designed and performed the experiments, derived the models and analysed the data. M.I., T.T and S.M. helped carry out the results. M.M. and G.K. wrote the manuscript in consultation.

Funding Open access funding provided by Università degli Studi di Palermo within the CRUI-CARE Agreement.

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Afshin T, Aliakbar A, Zhila S (2011) The use of electrocoagulation process for removal of turbidity, COD, detergent and phosphorus from carwash effluent. Water Wastewater 22:19–25

Agarwal P, Sangal VK, Mathur S (2024) Sequential electrocoagulation and electro-Fenton processes for the treatment of textile wastewater. Water Environ Res 96:e11118

Almeida CMVB Jr, Bonilla SH, Giannetti BF (2010) Identifying improvements in water management of bus-washing stations in Brazil. Resour Conserv Recycl 54:821–831

Al-Odwani A, Ahmed M, Bou-Hamad S (2007) Carwash water reclamation in Kuwait. Desalination 206(1–3):17–28

Ammar S, Oturan M, Labiadh L, Guersalli A, Abdelhedi R, Oturan N, Brillas E (2015) Degradation of tyrosol by a novel electro-Fenton process using pyrite as heterogeneous source of iron catalyst. Water Res 74:77–87

Barhoumi N, Oturan N, Olvera-Vargas H, Brillas E, Gadri A, Ammar S, Oturan M (2016) Pyrite as a sustainable catalyst in electro-Fenton process for improving oxidation of sulfamethazine. Water Res 94:52–61

Bhatti ZA, Mahmood Q, Raja IA, Malik AH, Khan MS, Wu D (2011) Chemical oxidation of carwash industry wastewater as an effort to decrease water pollution. Phys Chem Earth 36:465–469

Boluarte I, Andersen M, Pramanik B, Chang C, Bagshaw S, Farago L, Jegatheesan V, Shu L (2016) Reuse of car wash wastewater by chemical coagulation and membrane bioreactor treatment processes. Int Biodeterior Biodegrad 113:44–48

Boussu K, Kindts C, Vandecasteele C, Van der Bruggen B (2007) Applicability of nanofiltration in the carwash industry. Sep Purif Technol 54:139–146

Brillas E, Sirés I, Oturan MA (2009) Electro-Fenton process and related electrochemical technologies based on Fenton's reaction chemistry. Chem Rev 109(12):6570–6631

Cheng T, Huang C, Huang Y, Shih Y (2016) Kinetic study and optimization of Electro-Fenton process for dissolution and mineralization of ion exchange resins. Chem Eng J 308:954–962

Clematis D, Cerisola G, Panizza M (2016) Electrochemical oxidation of a synthetic dye using a BDD anode with a solid polymer electrolyte. Electrochem Commun 75:21–24

Díez AM, Rosales E, Sanromán MA, Pazos M (2017) Assessment of LED-assisted Electro-Fenton reactor for the treatment of winery wastewater. Chem Eng J 310:399–406

Fernandes A, Spranger P, Fonseca A, Pacheco MJ, Ciríaco L, Lopes A (2014) Effect of electrochemical treatments on the biodegradability of sanitary landfill leachates. Appl Catal B Environ 144:514–520

Garcia-Segura S, El-Ghenymy A, Centellas F, Rodriguez R, Arias C, Garrido J, Cabot P, Brillas E (2012) Comparative degradation of the diazo dye direct yellow 4. J Electroanal Chem 681:36–43

Garcia-Segura S, Eiband MMSG, de Melo JV, Martínez-Huitle CA (2017) Electrocoagulation and electro-Fenton in water and wastewater treatment: a critical review. J Environ Manage 801:267–299

Ghanbari F, Moradi M (2015) Comparative study of electrocoagulation and electro-Fenton processes. J Environ Chem Eng 3:499–506

Gregory J (2006) The role of ionic strength in water treatment processes. Colloids Surf A Physicochem Eng Asp 289(1–3):223–232

Isarain Chávez E, Garrido JA, Centellas F, Arias C, Rodríguez RM, Brillas E, Peralta Hernández JM (2014) Role of iron concentration on the electro-Fenton oxidation process. Electrochim Acta 133:242–248

Khan A, Khan S, Khan MA, Qamar Z, Waqas M (2015) The uptake and bioaccumulation of heavy metals by food plants, their effects on plant nutrients, and associated health risk: a review. Environ Sci Pollut Res Int 22:13772–13799

Khouni I, Marzouki M, Ksibi M (2020) Integrated electrochemical processes for textile industry wastewater treatment. Sustain Environ Res 30:1–11

Kiran KS, Arthanareeswaran G, LukkaThuyavan Y, Ismail A (2015) Influence of bentonite in polymer membranes for effective treatment of car wash effluent to protect the ecosystem. Ecotoxicol Environ Saf 121:186–192

Labiadh L, Fernandes A, Ciríaco L, Pacheco M, Lopes A (2016) Electrochemical treatment of concentrate from reverse osmosis of sanitary landfill leachate. J Environ Manage 181:515–521

Lau WJ, Ismail AF, Firdaus S (2013) Car wash industry in Malaysia. Sep Purif Technol 104:26–31

Loaiza-Ambuludi SA, Panizza M, Oturan N, Özcan A, Oturan MA (2013) Electro-Fenton degradation of anti-inflammatory drug ibuprofen in hydroorganic medium. J Electroanal Chem 702:31–36

Mollah MYA, Morkovsky P, Gomes JAG, Kesmez M, Parga J (2004) Fundamentals, present and future perspectives of electrocoagulation. J Hazard Mater 114(1–3):199–210

Moreira F, Garcia-Segura S, Vilar V, Boaventura R, Brillas E (2013) Decolorization of sunset yellow FCF. Appl Catal B Environ 142–143:877–890

Mousazadeh M, Niaragh EK, Usman M, Khan SA, SandovalA A-QZ, Khalid BZ, Gilhotra V, Emamjomeh MM (2024) A critical review of state-of-the-art electrocoagulation technique applied to COD-rich industrial wastewaters. Environ Sci Pollut Res 28(32):43143–43172

Panizza M, Cerisola G (2010) Applicability of electrochemical methods to carwash wastewaters. J Electroanal Chem 638:236–240

Páramo Vargas J, Estrada Camargo AM, Gutiérrez Granados S, Godínez LA, Peralta Hernández JM (2015) Electro-Fenton for slaughterhouse effluent. J Electroanal Chem 754:80–86

Sirés I, Brillas E (2017) Advanced oxidation processes based on electrochemical oxidation. Appl Catal B: Environ.

Sun YF, Pignatello JJ (1993) Photochemical reactions in mineralization of 2,4-D. Environ Sci Technol 27:307–310

Tamiazzo J, Breschigliaro S, Salvato M, Borin M (2015) Constructed wetland treating surfactant-polluted water. Environ Sci Pollut Control Ser 22:12816–12828

Thiam A, Zhou M, Brillas E, Sirés I (2014) Coupling electrocoagulation with EAOPs. Appl Catal B Environ 150–151:116–125

Ustun GE (2021) Advanced treatment of dye manufacturing wastewater. Journal of Environmental Chemical Engineering.

Zhou Z, Wei W, Wu H, Gong H, Zhou K, Zheng Q, Liu S, Gui L, Jiang Z, Zhu S (2024) Coupling electro-Fenton and electrocoagulation in aluminum–air batteries. Molecules 29(16):3781

Authors and Affiliations

Najwa Hamdi[1] · Ibtissem Boumnijel[2] · Mabrouk Mosbahi[3,4,5] · Khaled Gammoudi[4,5] · Ibrahim Mabrouki[5] · Baghdadi Aloui[6] · Marco Sinagra[3] · Tullio Tucciarelli[3]

✉ Mabrouk Mosbahi
mabrouk.mosbahi@unipa.it

[1] Electrochemistry, Materials and Environment Research Unit (UREME), Faculty of Sciences of Gabès, Erriadh City, University of Gabès, 6072 Gabès, Tunisia

[2] Laboratory of Wind Energy Management and Waste Energy Recovery, Research and Technology Center of Energy, B.P. 95, 2050 Hammam-Lif, Ben Arous, Tunisia

[3] Department of Engineering, University of Palermo, 90128 Palermo, Italy

[4] Higher Institute of Applied Sciences and Technology of Gafsa, University of Gafsa, 2112 Gafsa, Tunisia

[5] Laboratory of Electro-Mechanic Systems (LASEM), National School of Engineers of Sfax (ENIS), University of Sfax, Km 3.5 Soukra, B.P. 1173, 3038 Sfax, Tunisia

[6] Laboratory of Mathematics and Applications LR17ES11 Erriadh City, Higher Institute of Industrial Systems of Gabes, Gabes University Research, Zrig, 6072 Gabes, Tunisia