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Towards Sustainable Management of Construction Site Wastewater: A Case Study Using Electrocoagulation and Impedance Spectroscopy

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Abstract

Construction sites generate large volumes of contaminated wastewater, yet sustainable treatment solutions remain limited. This study presents a case study focusing on the wastewater produced from washing construction equipment at an industrial site in northern Morocco. Initial characterization revealed a chemical oxygen demand of 3125 mg O_2/L, a five-day biochemical oxygen demand of 980 mg O_2/L, and a total suspended solids concentration of 676 mg/L, values that exceed national discharge standards. An electrocoagulation process using aluminum electrodes was employed, alongside electrochemical impedance spectroscopy, to investigate the treatment mechanisms. Under optimal conditions (30 min at 142.85 A/m^2), the removal of chemical oxygen demand reached 88%, alongside significant reductions in dissolved solids and electrical conductivity. Analysis of the electrochemical impedance spectroscopy identified two relaxation phenomena associated with ionic migration and flocculation, with efficiency decreasing beyond 0.3 A. These results demonstrate that electrocoagulation is an effective and sustainable technology for treating construction site wastewater. This study highlights its potential for practical application in the built environment and its relevance for improving the environmental performance of the construction sector.

Keywords: construction site wastewater; sustainable wastewater treatment; electrocoagulation; electrochemical impedance spectroscopy (EIS); built environment

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1. Introduction

The use of water resources is excellent for the survival of all human societies globally. Over the last several years, there has been an increasing concern about global water scarcity. This is due to an increased global population, extended business expansion (increased consumer needs), and increasing overall quality of life in developed and developing countries [1,2]. Climate change, continuing urbanization, and industrialization of cities and other built environments have all contributed to the death of aquatic ecosystems. Nutrient over-enrichment is one of the major contributors to the death of aquatic algae (i.e., eutrophication of water bodies) [3,4]. Sustainable water use management is, therefore,

crucial for many economic sectors. However, the construction industry has added to the rapidly growing demand for water but has created considerable amounts of wastewater, which, relatively speaking, it has not researched and provided potential use with respect to how water is consumed and affected by construction and related activities but continues to increase its negative impact on water resources.

The growing economies of the world are driven by the increased economic growth of developing economies and continue to expand, increasing the production of goods and services to meet demands from the global marketplace. In many situations, the economic growth created by industrial expansion (especially in developing economies) is contributing to the deterioration of the global environment and biodiversity because of the continued discharge of significant amounts of untreated industrial wastewater into the environment [5,6]. As a result, the chemicals in these industrial effluents will create an adverse impact on the environment, human health, and quality of soil and water, thereby degrading the environmental quality.

Morocco's construction industry has seen rapid growth over the last few years. The construction industry had an estimated output of 80.5 billion dirhams (approximately 7.7 billion United States dollars) in 2022, which played a significant role in Morocco's gross domestic product, ranking it fifth among Arab Nations in GDP contribution from construction [7]. With upcoming important events, such as the Africa Cup of Nations 2025 and the FIFA World Cup 2030, this upward trend is expected to continue [8]. However, in addition to the increase in construction activity, the increase in wastewater produced during construction increases the need for effective management of wastewater as a means of improving the environmental performance of the industry and implementing sustainable construction methods.

Research has not yet established any significant relationships between the environmental impact of construction site wastewater treatment and management and the existing techniques, which are limited due to the operational restrictions that must be taken into consideration when addressing site conditions (e.g., variability, complexity, type) when treating and managing effluents. This lack of research demonstrates a need for further exploration into the processes involved in treating and managing construction site wastewater and will examine the potential for using electrocoagulation (EC) to treat construction equipment wash water at the construction site, as well as utilizing electrochemical impedance spectroscopy (EIS) to study the electrochemical processes involved in EC with construction equipment wash water. Theoretical issues regarding water sustainability and reuse will also be discussed in relation to integrating EC into sustainable onsite water management solutions.

The construction industry consumes a sizable amount of water, accounting for roughly 16% of all freshwater used by humanity [9,10]. It uses water as a raw ingredient in many products, as well as for cooling various pieces of equipment (tunnel borers, drills/cutting equipment), and cleaning various types of machinery and tools. These activities produce waste that contains fine solids, chemicals, and other pollutants that can harm soils and water if discharged untreated.

For large-scale or complex construction projects, liquid waste is produced at an estimated average rate of 20 L/min during the construction phase, which could potentially cause contamination of groundwater, damage drinking water supplies, and damage local biodiversity [11–14]. In some jurisdictions, construction contractors are encouraged or required to implement sustainable water management methods to minimize the impact on the environment and maximize the reuse of resources.

Wastewater treatment is necessary for the control of pollution and conservation of natural resources. The methods for wastewater treatment include membrane filtration [15,16], advanced oxidation processes [17,18], biological treatment systems [19], and electrocoagulation (EC), which is starting to attract more interest because of its relative simplicity and low cost [20,21].

Sustainable construction practices are mainly concerned with efficient and recyclable materials, while also enhancing water management systems. Sustainable construction practices use waste materials from construction and demolition sites in circular economic management. The use of recycled construction materials is becoming increasingly popular as alternatives to natural raw materials. Fully recycled alkali-activated mortars are produced from fine waste concrete and used as a replacement to both cementitious binders and natural sand and have shown good mechanical performance, durable performance, and contribution to the environment [22]. Advanced characterization techniques were used to measure how mechanical behavior changes over time and to determine mechanisms of degradation. An example of this is the use of in situ four-dimensional computed tomography (4D CT) to examine the development of micro-cracks in recycled aggregate concrete containing fiber reinforcement in the presence of carbon dioxide and to provide a better understanding of mechanical performance and damage mechanisms [23]. Overall, recycled construction materials could play an important role in furthering sustainable practices in construction and protecting natural resources. Nonetheless, integrating these approaches into a sustainable water management plan for sites has not been thoroughly explored.

This study builds upon previous research conducted in Casablanca (Sidi Bernoussi) at a CAPEP construction site where collection basins were installed for the treatment of liquid discharge [24]. This operational context enables the evaluation of treatment solutions adapted to real construction site conditions, as well as the analysis of their potential contribution to improving environmental practices in the construction sector.

In this study, we provide a case study looking at equipment wash and cleaning operations and characterizing the wastewater from these processes to study the feasibility of electrocoagulation (EC) as a sustainable and environmentally friendly treatment method for the wash water. In the EC treatment method, coagulants are produced in situ that neutralize the charges of suspended solids and colloids, which allows for flocculation and increases the rates of removal of contaminants [25,26]. The EC treatment method was optimized for current density and conductivity by using electrochemical impedance spectroscopy (EIS) to determine the conduction mechanisms [27,28].

The three main research questions of this study are as follows: (a) How effective is EC as a treatment option for wash waters produced at construction sites? (b) What are the electrochemical mechanisms that were identified from EIS? (c) How can this process support sustainable water management and more environmentally friendly construction practices?

2. Materials and Methods

2.1. Site of the Sampling

The survey and sampling company is located in the rural commune of Bouskoura, southeast of Casablanca, on the Mediouna Road (km 9). The site is located in the Hay Inara Aïn Chock (Hay Hassani) area.

2.2. Sampling and Analysis Conditions

Wastewater samples were collected manually from the inspection chamber located upstream of the treatment system, before any depollution stage took place. No automatic sampling devices were used during this campaign. Grab samples were collected at regular

intervals and combined to form a 24 h composite sample, ensuring an accurate assessment of the wastewater produced by the company's equipment washing activities. At the time of the study, the company was carrying out an underground gallery construction project, which influenced the characteristics and volume of the wastewater produced. The inspection chamber had an effective volume of 6 m^3, and the wastewater flow rate at the sampling point was approximately 3 m^3/h, corresponding to the system's peak flow. This sampling strategy allowed hourly variations in the wastewater stream to be accurately captured.

Samples were preserved and transported in accordance with the experimental protocol and the Moroccan standard NM ISO 5667-1 (2012), which provides guidelines for designing sampling programs and techniques for assessing water quality. The samples were stored in opaque containers to protect them from light and preserve their physicochemical characteristics and were kept at 4 °C until analysis. Physicochemical and biological analyses were performed within 24 h of sampling.

Key physicochemical parameters, including pH, electrical conductivity (EC), total suspended solids (TSS), chemical oxygen demand (COD), five-day biochemical oxygen demand (BOD_5), and chlorides (Cl^-), were measured in samples collected in polyethylene bottles according to relevant AFNOR standards. Additionally, total dissolved solids (TDS), usable solids potential (USP), and oxidation–reduction potential (ORP) were measured using a Hanna HI98194 portable multiparameter device, which allows the simultaneous monitoring of multiple water quality parameters.

Samples were collected in sterilized glass bottles to prevent contamination for the determination of metallic elements such as iron (Fe), arsenic (As), and zinc (Zn), as well as other trace elements. Analyses were performed using atomic absorption spectrometry (AAS) with a PerkinElmer Analyst 400 spectrometer. This instrument is widely used for quantifying trace metals in wastewater and is recognized for its high sensitivity and precision.

2.3. Electrocoagulation Process

Electrocoagulation (EC) is a water treatment method based on electrolysis, a process that involves decomposing or changing substances using an electric current [29]. The EC system consists of pairs of metallic electrodes connected in series or parallel to a power source to produce metal ions and neutralize or remove impurities. The most frequently used anode/cathode combinations are aluminum, iron, and stainless-steel electrodes, as they are widely employed due to their ease of use, efficiency, low cost, and safety [30,31].

Current flows from the anode through the electrochemical corrosion reaction, releasing free metal cations, while at the cathode, it produces hydroxides and hydrogen gas. These metal cations then react with hydroxides to produce metal hydroxides or metal sulfides with a high surface area, which then coalesce with the dissolved impurities [29]. At the same time, the hydrogen bubbles produced by the evolved hydrogen gas transport suspended solids to the surface for removal [32].

The following chemical equations (Equations (1) and (2)) represent the stoichiometric equations associated with the use of aluminum electrodes in the electrocoagulation (EC) process:

$$\text{Anode: Al (s)} \rightarrow \text{Al}^{3+}\text{ (aq)} + 3\,\text{e}^- \quad (1)$$

$$\text{Cathode: } 3\,\text{H}_2\text{O} + 3\,\text{e}^- \rightarrow {}^3/_2\,\text{H}_2\text{ (g)} + 3\,\text{OH}^- \quad (2)$$

Figure 1 shows the electrocoagulation (EC) experimental setup used in this paper. The effect of current density was evaluated by varying the current from 0.1 A to 0.4 A, with all

experiments conducted using a 200 mL batch of effluent at an approximate temperature of 25 °C (within a range of ±2 °C). Initial tests used two flat aluminum electrodes with active areas of 21 cm^2 when connected in parallel with 2 cm spacing to reduce ohmic losses [33].

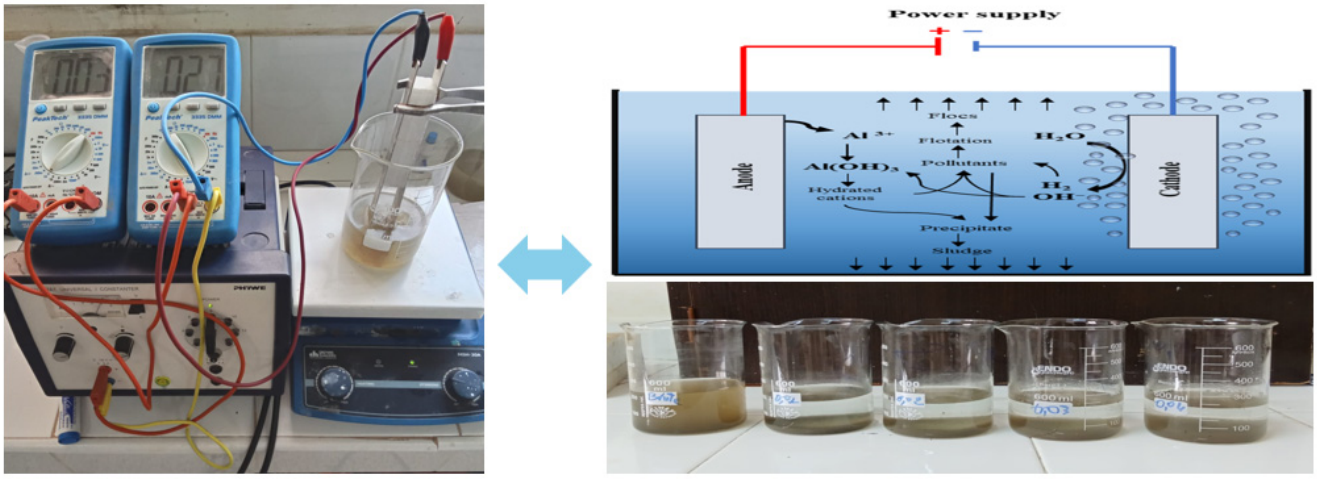

Figure 1. Experimental setup of the electrocoagulation process and illustration of the progressive clarification of raw wastewater under different applied current densities.

Prior to the experiments, the aluminum electrodes were conditioned and connected to a low-voltage direct current power supply until a continuous electric current was established. During the experiments, the solution was kept homogeneous using a magnetic stirrer at 200 rpm. After electrocoagulation, the stirrer was stopped and the suspensions were allowed to settle for 30 min. The floc was then allowed to sediment, after which the clarified supernatant was removed and centrifuged for subsequent analysis.

2.4. Electrochemical Impedance Spectroscopy (EIS)

Electrochemical impedance spectroscopy (EIS) is arguably the most widely used advanced technique for investigating the properties of electrochemical systems [34,35]. It has been used for various purposes, such as assessing electrochemical performance [36], predicting temperature [37], and studying age-related phenomena [38]. EIS involves determining the impedance of a system by applying a time-varying sinusoidal potential at various frequencies and amplitudes. Nyquist plots, which are derived from the EIS response, include important information about the electrochemical processes occurring across the surface of the electrodes [39].

Due to its sensitivity and non-invasiveness, EIS is used to monitor electrocoagulation and flocculation in real time during wastewater treatment. EIS measurements allow the electrical response of the medium to be monitored at many different frequencies, providing a means of monitoring conductivity and resistance variability associated with floc formation and aggregation. Thus, EIS can provide important information on coagulation kinetics, colloidal particle stability, and treatment efficiencies and should be regarded as a significant enhancement to conventional analytical methods.

This study employed EIS measurements after 30 min of preconditioning. Measurements were taken over a frequency range of 100 Hz to 100 kHz at an AC potential amplitude of 100 mV using a potentiostat (HP Solartron Analytical). Measurements were taken using a two-electrode stainless-steel cell, and the data were analyzed using ZView 2.2 to obtain several electrical parameters.

3. Results and Discussion

3.1. Assessment and Characterization of Construction Site Wastewater

Prior to electrochemical treatment, a representative sample of wastewater generated from equipment washing operations at an underground tunnel construction site was analyzed to assess its quality. Tables 1 and 2 summarize the average physicochemical characteristics of the wastewater.

Table 1. Characterization of heavy metals in our untreated wastewater sample.

Parameter	Concentration in mg/L	Moroccan Standard
Arsenic (As)	0.5752	0.1
Cadmium (Cd)	Undetectable	0.25
Cobalt (Co)	0.0025	0.5
Total Copper (Cu)	0.0042	2
Total Lead (Pb)	0.0056	1
Total Chromium (Cr)	Undetectable	2
Total Tin (Sn)	Undetectable	2.5
Manganese (Mn)	0.0870	2
Total Nickel (Ni)	0.041	5
Selenium (Se)	0.0127	0.1
Total Zinc (Zn)	Undetectable	5
Iron (Fe)	0.4559	5
Total Phosphorus (F)	2.55	15
Aluminum (Al)	0.0275	10
Fluoride (F^-)	0.27	20

Table 2. Characterization of physicochemical parameters in our untreated wastewater sample.

Parameter	PH	CE	COD	BOD_5	TSS
Found value	7.4	1295	3125	980	676
Moroccan standard	5.5–9.5	2700	500	100	50

3.1.1. Heavy Metals, Trace Elements, and Nutrients

The arsenic concentration (0.575 mg/L) is significantly higher than the Moroccan standard of 0.1 mg/L, posing a serious environmental risk. Levels of other heavy metals (tin, chromium, and cadmium) are either very low or undetectable, and well below regulatory thresholds. Moderate concentrations of iron (0.456 mg/L), manganese (0.087 mg/L), and nickel (0.041 mg/L) have been found, consistent with the presence of materials and mechanical wear.

Additional nutrients contributing to the overall effluent load include aluminum (0.0275 mg/L) and total phosphorus (2.55 mg/L), both of which are present at low concentrations below regulatory limits. These results align with those of Andrić et al. [40] and Perera et al. [11], who observed that heavy metals and trace elements are often present in washing waters associated with metallic structures and mechanical processes.

3.1.2. Physicochemical Parameters

A pH of 7.40, which is considered neutral, falls within the legal limits for direct discharge (5.5–9.5) [41]. An electrical conductivity of 1295 µS/cm indicates higher mineralization and a high concentration of dissolved ions [42]. A total dissolved solids (TDS) level of 193 mg/L indicates a significant ionic charge in the wastewater. Additionally, an oxidation–reduction potential (ORP) of 167.4 mV indicates that the water is moderately oxidizing, while a usable solid potential (USP) of 0.18 indicates the presence of dissolved organics. The fluoride level of 0.27 mg/L was also low and well below the legal limit.

In comparison, the level of organic pollution is considerable:

- COD: 3125 mg O_2/L, reflecting a high quantity of total organic matter [43].
- BOD_5: 980 mg O_2/L, indicating the biodegradable fraction of this organic matter [44].
- TSS was 676 mg/L, confirming a considerable load of solid particles from cleaning operations and material wear [45].

These three parameters far exceed Moroccan standards. The COD/BOD_5 ratio of 3.18 reflects the high presence of complex organic matter that would biodegrade poorly by biological means. In relation to operational issues, extra physicochemical treatments (such as electrocoagulation or coagulation–flocculation) could be considered useful alternatives. Electrocoagulation would eliminate both COD and BOD_5 from the waste, enabling the effluent to meet or exceed legal requirements and making it more suitable for further biological treatment.

3.2. Effect of Current Density on the Efficiency of the EC Process

The efficiency of the electrocoagulation process was evaluated by measuring all the parameters listed above at various applied current values over a period of 30 min (see Table 3).

The specific energy consumption (SEEC) and the electric current density (J) were determined using Equations (3) and (4), respectively:

$$SEEC = (U \cdot I \cdot t)/(C0 - Cf)\ V) \quad (3)$$

where U is cell voltage; I is current; t is electrolysis time; C0 and Cf are initial compound concentration and final compound concentration, calculated from COD, at times 0 and t, respectively; V is volume of the solution to be treated.

$$J = I/A \quad (4)$$

where I is the electric current flowing through the system, expressed in amperes (A), and A is the surface area of the electrode through which the current flows, expressed in square meters (m^2).

Table 3. Physicochemical parameters of wastewater as a function of applied electric current intensities.

I/A	U/V	J/A/m^2	R/%	COD/mg/L	PH	EC/µS/cm	TDS/mg/L	ORP/mV	USP	SEEC/kwh/kg
0	0	0	0	3125	7.40	1295	193	167.4	0.18	0
0.1	1.5	47.61	35.97	2001	7.13	1210	183	142.4	0.17	0.333
0.2	2.2	95.23	71.80	881	7.44	1098	146	129.7	0.14	0.49
0.3	4.5	142.85	88	375	7.66	982	136	120.1	0.13	1.22
0.4	8.6	190.47	87.93	377	7.8	983	131	104.8	0.13	3.129

Notes: I = Current, U = voltage, J = current density, R = COD removal efficiency, EC = electrical conductivity, TDS = total dissolved solids, ORP = oxidation–reduction potential, USP = usable solid potential, SEEC = specific energy consumption per kg of COD removed.

3.2.1. Influence of Electric Current Intensity on the Removal Efficiency of Chemical Oxygen Demand (COD) in Wastewater

A measure of pollution levels and meeting discharge standards is chemical oxygen demand (COD). Electrocoagulation (EC) provides effective treatment through enhanced electrode dissolution, promoting the creation of metal hydroxides and polymer complexes to promote both co-precipitation and sweeping coagulation of contaminants [46,47]. According to Figure 2, as the current increases, so does the rate of COD removal, reaching 88% within 30 min when using 0.3 A (142.85 A/m^2). These findings align with previous studies evaluating the application of EC processes to industrial effluents, generally providing COD removal efficiencies between 80% and 95% [48–50].

However, an analysis of the process performance reveals an important techno-economic trade-off. While increasing the current density from 47.61 A/m^2 to 190.47 A/m^2 improves COD removal from 35.97% to 87.93%, this is accompanied by a substantial increase in specific energy consumption, rising from 0.333 to 3.129 kWh/kg of COD removed—nearly a tenfold

increase. Beyond 0.3 A, the marginal gain in treatment efficiency is disproportionate to the additional energy cost. This significant increase in energy consumption, which is often associated with electrode polarization and secondary reactions such as hydrogen evolution, indicates that 0.3 A is the optimal operating point for this system from a techno-economic perspective. Furthermore, as reported in other studies, complete COD removal remains difficult to achieve using electrocoagulation alone. Pursuing higher removal efficiencies would result in an energy footprint that is not economically viable on an industrial scale.

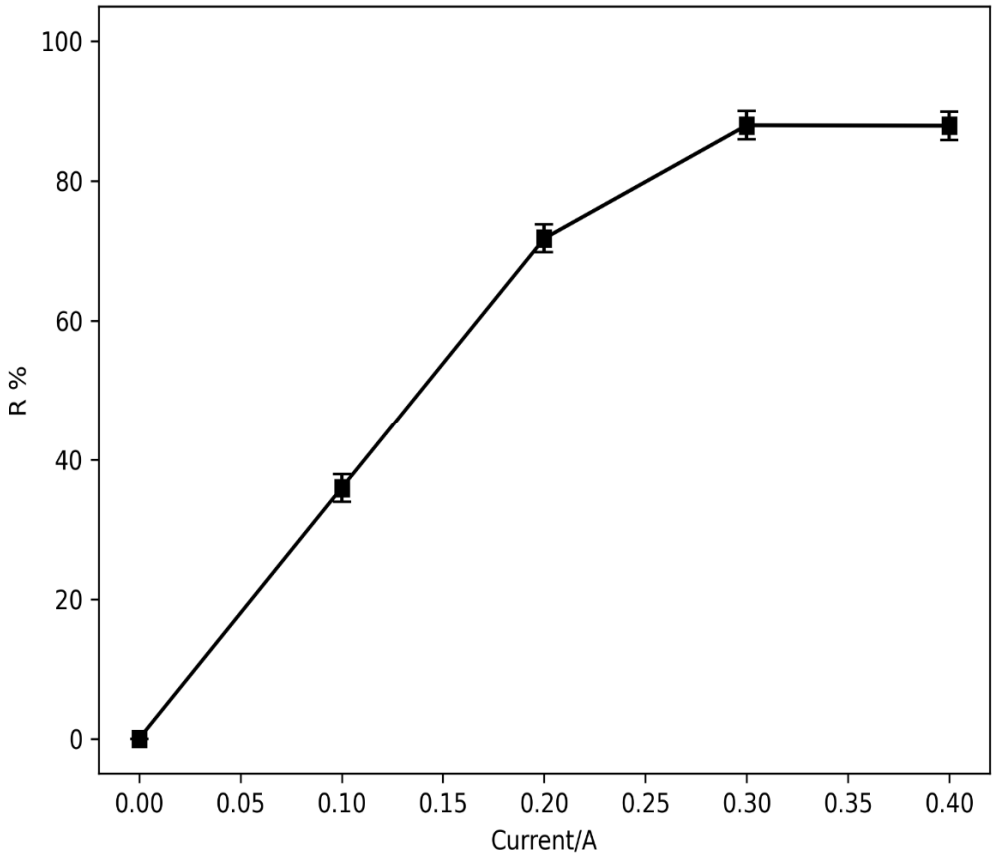

Figure 2. Effect of applied current on COD removal efficiency (R%) in wastewater (mean ± standard deviation).

From a practical and industrial perspective, these results should be interpreted in terms of relative environmental benefit rather than absolute treatment sustainability. The present study was conducted at laboratory scale; therefore, further pilot-scale investigations are required before industrial implementation can be recommended. In the context of construction site wastewater management, the proposed process could be considered as an onsite treatment option for large construction projects, where wastewater generation is significant. However, economic feasibility, reactor scale-up, and operational maintenance costs must be evaluated before large-scale deployment. Future work should focus on process optimization, cost modeling, and integration of the treatment system within construction site wastewater management strategies.

3.2.2. Influence of Electric Current Intensity on the Evolution of Total Dissolved Solids (TDS) and Electrical Conductivity in Wastewater

The development of total dissolved solids (TDS) and electrical conductivity (EC) in wastewater from the cleaning and washing of CAPEP construction equipment was examined based on the current density applied in the electrocoagulation process (see Figure 3). The electrocoagulation process began with a TDS level of 193 mg/L

and finished with a TDS level of 131 mg/L. The initial EC level was 1295 µS/cm, dropping to 983 µS/cm by the end of the experiment. The reduction in charged particle concentration due to electrocoagulation caused a significant drop in TDS, which was enhanced by sonication, resulting in variances in interparticle interactions and saturation of the resultant coagulation [51].

Increased current density incites electrochemical and electrocoagulation reactions that continually consume specific dissolved ions through precipitation or coagulation. This decreases the concentration of dissolved solids in the water, leading to a reduction in TDS and, subsequently, the electrical conductivity of the water [52].

3.2.3. Influence of Electric Current Intensity on the Evolution of TSS and ORP in Wastewater

Figure 4 illustrates the variation in usable solid potential (USP) and oxidation–reduction potential (ORP) in wastewater generated from the washing and cleaning of CAPEP construction machinery as a function of the applied diffusion-controlled current density during electrocoagulation. The USP, which represents the fraction of recoverable or potentially reusable solid matter in the effluent, decreased from 0.18 to 0.13, indicating a significant reduction in the usable solid load due to electrochemically induced coagulation and flocculation mechanisms.

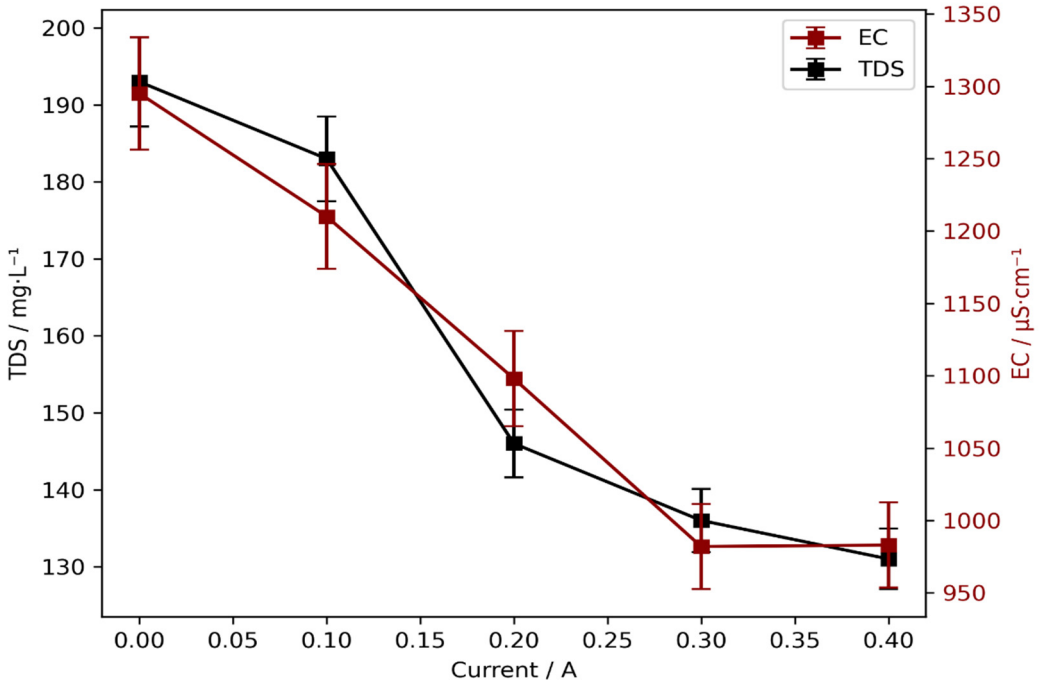

Figure 3. Changes in total dissolved solids (TDS) and electrical conductivity (EC) of construction site wash water with applied current density (mean ± standard deviation).

Meanwhile, the oxidation–reduction potential (ORP) decreased from 167.4 mV to 104.8 mV, reflecting a reduction in the oxidizing character of the medium, likely resulting from the consumption of oxidizing species and changes in redox equilibrium during treatment. The simultaneous decrease in both USP and ORP confirms the effectiveness of the electrocoagulation process in reducing recoverable solid fractions and improving the overall quality of the treated effluent.

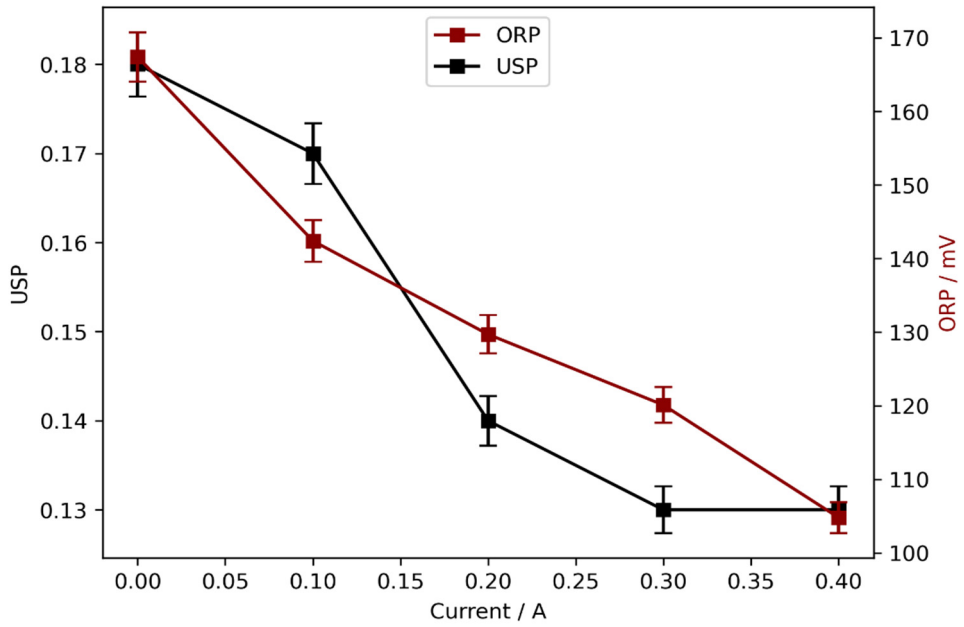

Figure 4. USP and ORP variations in construction site wash water under different applied current densities (mean ± SD).

3.3. Study of the Electrocoagulation Process Using Electrochemical Impedance Spectroscopy (EIS)

Figure 5a shows the variation in the imaginary part of the AC conductivity of wastewater versus the real part during the electrocoagulation (EC) process at different applied current intensities. Two distinct relaxation processes can be seen: the first relaxation (high-frequency arc) and the second relaxation (low-frequency arc). The high-frequency arc corresponds to bulk electrolyte behavior, reflecting ion mobility and charge transfer in the wastewater. As the current increases, this arc shifts, indicating changes in conductivity due to the formation of aluminum hydroxide flocs, which absorb ionic species and reduce overall conductivity. The low-frequency arc represents interfacial phenomena such as electrode polarization and floc resistance. Its growth at higher currents suggests increased floc density, hindering ion movement and raising interfacial resistance, particularly beyond the critical threshold of 0.3 A.

These observations align with those of Aarfane et al. [53], who attributed similar dual relaxation mechanisms in EIS spectra to ion mobility and floc formation in aluminum-based EC systems.

Figure 5b presents the frequency dependence of the real part of the AC conductivity (σ') of the wastewater during electrocoagulation at varying current intensities (0–0.4 A). In the high-frequency range (>1 kHz), conductivity remains relatively stable, reflecting bulk electrolyte behavior where ion mobility dominates. As the frequency decreases (below 100 Hz), significant dispersion occurs due to interfacial polarization effects at the electrode surfaces and within the growing floc networks. Conductivity systematically decreases with increasing current, demonstrating the progressive adsorption of ionic species onto aluminum hydroxide flocs, a well-documented phenomenon in the EC literature [51].

Figure 5c shows the imaginary part of ac conductivity (σ'') as a function of frequency for various applied current intensities (0–0.4 A). Two distinct relaxation processes are observed: (1) high-frequency relaxation (>1 kHz), which is attributed to ionic mobility in the solution; and (2) low-frequency relaxation (<100 Hz), which is related to interfacial phenomena at the electrodes and floc resistance. This is consistent with similar studies [51]. These two relaxation regimes confirm the dual mechanism controlling electrocoagulation efficiency: ionic transport in the solution and charge transfer resistance at the interfaces.

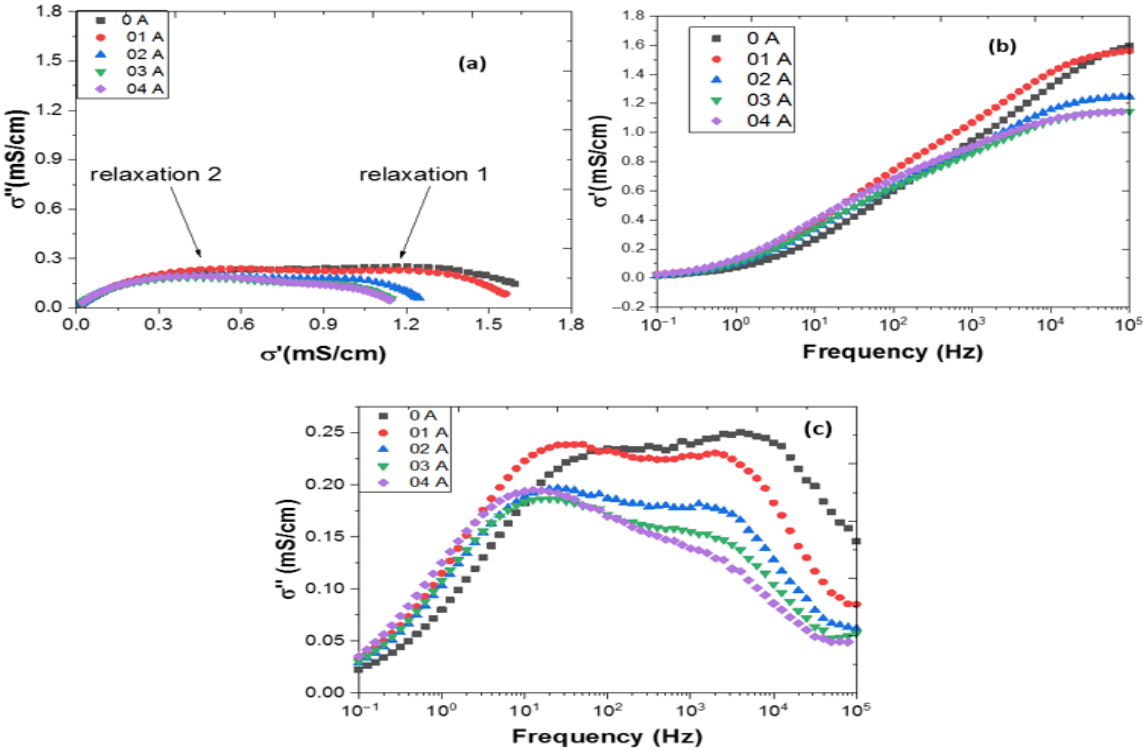

Figure 5. Conductivity spectra: (**a**) Nyquist plot and (**b**,**c**) Bode plots of wastewater electrocoagulation at different applied intensities.

3.3.1. Modeling via Electrical Equivalent Circuit

As shown by the excellent fit to the experimental data, the equivalent circuit model (R1-CPE1||R2-CPE2) accurately describes the two different relaxation processes of the electrocoagulation system in Figure 6. High-frequency relaxation (R1-CPE1) corresponds to charge transfer resistance and double-layer capacitance at the electrode–electrolyte interface. In contrast, low-frequency relaxation (R2-CPE2) represents diffusion-controlled processes and flocculation in the bulk solution. The quality of the fit indicates that the model accurately describes the system's electrochemical behavior, with the constant phase elements (CPEs) accounting for surface inhomogeneity and non-ideal capacitive effects. The derived circuit parameters could provide valuable insights into the electrocoagulation process's kinetics and how floc structures evolve with varying operating conditions.

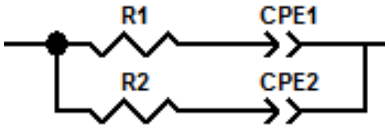

Figure 6. Equivalent electrical circuit.

The deconvolution of the conductivity spectra clearly distinguishes between the contributions of the high-frequency (bulk solution) and low-frequency (interfacial) relaxation processes (see Figure 7). High-frequency relaxation reflects the intrinsic ionic conductivity of wastewater, while low-frequency relaxation is indicative of polarization effects from growing floc networks. This deconvolution approach is a powerful tool for quantifying the relative importance of bulk versus interfacial phenomena in controlling the overall electrocoagulation efficiency and could be used to optimize process parameters for specific wastewater treatment applications.

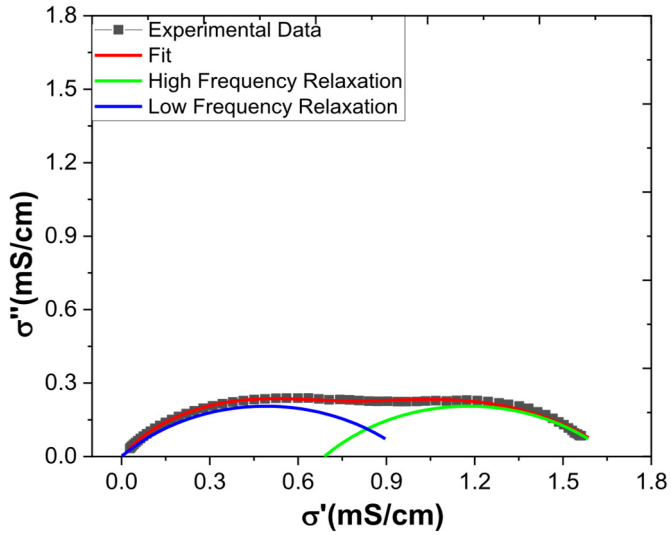

Figure 7. Experimental data and deconvolution process using an electrical equivalent circuit and Nyquist conductivity spectrum.

3.3.2. Optimization of Applied Current Intensity (I) During Electrocoagulation Process

Figure 8a shows the relationship between the applied current intensity and the electrochemical parameters (R_1 and τ_1) that control the electrocoagulation process. At low current intensities (below 0.3 A), R_1 decreases slightly due to the increased mobility of ions resulting from electrolytic reactions that facilitate charge transfer within the wastewater matrix. Concurrently, τ_1 decreases, indicating accelerated charge transfer dynamics at the electrode–electrolyte interface. This behavior reflects the improved electrochemical reactivity associated with a moderate current supply, which promotes the controlled dissolution of aluminum electrodes and the efficient generation of coagulants.

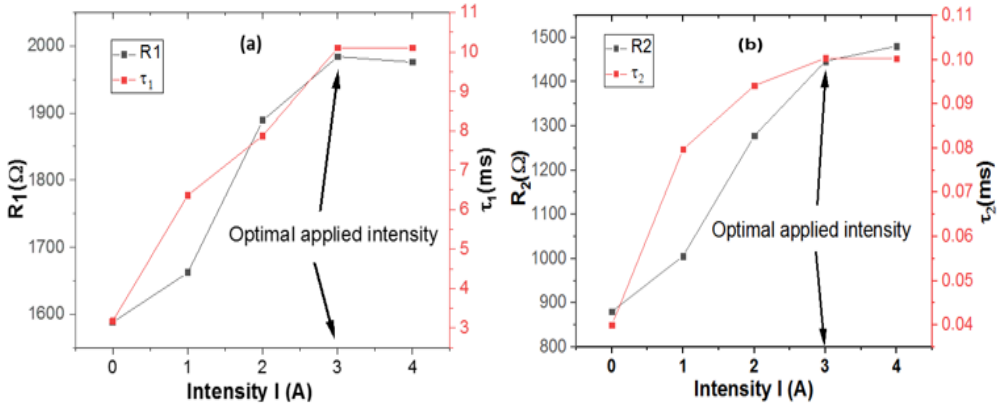

Figure 8. Relationship between the applied current intensity (I) and the electrochemical parameters deduced from the equivalent electrical circuit during electrocoagulation.

Beyond the critical threshold of 0.3 A, however, both R_1 and τ_1 increase sharply. This trend is primarily due to the progressive formation of aluminum hydroxide flocs, which increase the resistive nature of the medium by creating physical and electrochemical barriers to ion transport. Dense floc networks adsorb dissolved species and hinder ionic diffusion, leading to higher polarization resistance and longer relaxation times. These observations are consistent with the dual relaxation mechanisms identified by electrochemical impedance spectroscopy (EIS), whereby high-frequency responses are associated with ionic conduction in the bulk solution and low-frequency responses reflect interfacial polarization and floc resistance phenomena [51].

Figure 8b illustrates the evolution of interfacial resistance (R_2) and relaxation time (τ_2) in relation to the applied current intensity. The monotonic increase in R_2 from 800 Ω to k 1500 Ω confirms the progressive development of impedance induced by aluminum hydroxide floc formation. This phenomenon is particularly pronounced at higher current densities, where accelerated electrode corrosion promotes the rapid precipitation of metal hydroxides. Concurrently, the relaxation time (τ_2) decreases from 0.11 s to 0.04 s, indicating faster charge dissipation at the electrode–solution interface due to the stronger electric field compressing the electrochemical double layer. These behaviors are consistent with electrocoagulation mechanisms reported in the literature [51], in which floc network formation has a significant influence on impedance characteristics.

The dual trends observed in R_1, R_2, τ_1, and τ_2 confirm that the efficiency of electrocoagulation is governed by a balance between ionic mobility and flocculation dynamics. These results are consistent with previous studies demonstrating that electrocoagulation performance is regulated by coupled processes involving charge transfer kinetics and mass transport phenomena [51]. Identifying two relaxation regimes confirms that electrocoagulation operates through simultaneous mechanisms involving both bulk solution conductivity and interfacial electrochemical reactions.

The optimal operating point, which was observed at around 0.3 A, represents a practical compromise between the efficiency of the treatment process and energy consumption. Below this threshold, insufficient coagulant is produced to effectively destabilize pollutants. Conversely, operating above this threshold results in diminishing returns in terms of removal efficiency, despite increased energy expenditure. This is mainly due to competitive side reactions, such as oxygen evolution, and increased ohmic losses. Similar trends have been widely reported in electrocoagulation systems treating wastewater with a high organic load [45–47].

Electrochemical impedance behavior provides important mechanistic insight into process optimization. Dual relaxation phenomena indicate that treatment efficiency is controlled by ionic transport within the wastewater and by polarization effects associated with floc growth and aggregation. Therefore, optimizing electrocoagulation requires balancing electrochemical kinetics with mass transport limitations.

From a practical perspective, these findings have significant implications for large-scale implementation. For future scale-up applications, it is essential to maintain a similar current density rather than a fixed current value in order to preserve comparable electrochemical operating conditions in larger reactors. This strategy ensures consistent pollutant removal efficiency while limiting operational energy costs, which is particularly important for sustainable wastewater treatment applications in the construction sector.

4. Conclusions

The construction sector uses a lot of water, meaning that water is required for many tasks. However, this enormous use also leads to the production of a lot of wastewater, which is typically produced from washing tools, etc. This wastewater then reaches many different areas, including surfaces and groundwater, causing major environmental problems for construction projects. Thus, it is important to manage and treat these effluents correctly in order to decrease the environmental impact of construction activity.

This research examined a construction activity that was undertaken in Casablanca, Morocco, using CAPEP's wastewater management system as an example of how well waste was being managed at one specific collection and treatment location. The research was a characterization of the effluent produced from washing tools and evaluated how effective the electrocoagulation (EC) process was at reducing the pollutant load. The research found

that electrocoagulation was very successful at removing organic contaminants from effluent, allowing for improvement in treated effluent quality.

The investigation through electrochemical impedance spectroscopy analysis produced two clear separation processes in two frequency ranges. The fast process describes the ionic transportation through a liquid medium; however, the slow process is an indication of electrode polarization as well as flocculation. At a current above 0.3 A, there is a significant increase in the total interfacial resistance from 800 Ω to 1500 Ω. This increase may limit the overall efficiency of the treatment process. Therefore, future works could look for other waste treatment options that could improve the total COD removal rates and/or improve the energy efficiency and/or minimize the electrical consumption of the electrocoagulation process.

Three significant scientific contributions to knowledge are presented in this work. First, it thoroughly characterized the construction wash water generated from washing equipment within the Moroccan industrial situation. This strongly underreported source of wastewater currently has little representation in the literature. Second, it demonstrated the ability of EC to treat this wastewater. Finally, combining EIS with existing knowledge of electrochemical principles expanded our understanding of electrochemical mechanisms and relaxation mechanisms associated with general electrochemical processes, which will improve technology development for electrochemical processes, contributing to more sustainable methods for managing construction wash water.

These findings show promise but still have a number of limitations. One example is that EC has higher energy requirements at increased current densities, which can affect its potential use onsite. Although initial assessments of sustainability are positive, more research should be conducted to create a comprehensive lifecycle assessment and to develop a strategy for managing sludge from EC while comparing it with other treatment options.

Future research efforts should focus on pilot-scale studies, the incorporation of EC into construction processes, and the creation of circular water strategies to maximize both environmental and operational benefits. By addressing these issues, EC could become a viable solution for the sustainable management of construction wastewater and contribute to building in a more environmentally responsible manner.

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