

Sustainable electrocoagulation of amoxicillin using commercial mild steel and mild steel recycled from food cans: A comparative kinetic and adsorption-modelling study

Mohammed A. A. Al-Ameri^{1*} , Ghayda Yaseen Al Kindi¹ 

¹ College of Civil Engineering, University of Technology – Iraq, Alsinaa Street 52, Baghdad 10066, Iraq

* Corresponding author's e-mail: mohammed.a.abdulfattah@uotechnology.edu.iq

ABSTRACT

Commercially available mild steel (CMS) electrodes and electrodes recycled from waste tomato paste cans (recycled mild steel, RMS) were compared in an electrocoagulation reactor treating amoxicillin in aqueous solution. Both materials were characterised by scanning electron microscopy, and the operating conditions were optimised one factor at a time: initial pH (5, 7, 8), initial concentration (10, 25, 50, 100 mg/L), inter-electrode distance (1.0, 1.5, 2.0 cm) and applied voltage (5, 10, 15, 20 V). The optimum was pH 7, 1 cm spacing and 15 V, under which removal exceeded 99% for both materials: 99.4% for the recycled electrode and 99.3% for the commercial one. Over the full 90-minute treatment the corresponding specific energy consumption was 32.06 and 32.63 kWh/m³ respectively. Removal followed pseudo-first-order kinetics on both materials, the apparent rate constant falling from 0.038 to 0.019 min⁻¹ as the initial concentration rose from 10 to 100 mg/L. The concentration dependence at 90 minutes was described best by the Langmuir isotherm, with an apparent monolayer capacity of 76.5 mg/g of dissolved iron for the recycled electrode and 72.3 mg/g for the commercial one; equilibrium was not reached within this time, so these capacities are lower bounds. Electrodes recovered from discarded food cans therefore remove amoxicillin from the aqueous phase as effectively as commercial mild steel while diverting a waste stream from disposal, a practical contribution to the circular economy. Removal denotes transfer of the antibiotic into the iron hydroxide floc rather than degradation, which was not measured.

Keywords: amoxicillin removal, electrocoagulation, recycled mild steel electrodes, adsorption kinetics, adsorption isotherms, circular economy.

INTRODUCTION

The greatest environmental challenge of the 21st century has emerged from the active pharmaceutical ingredients (APIs) that cause water pollution. Among these pollutants, amoxicillin (AMX) — a broad-spectrum beta-lactam antibiotic — stands out as a major threat to aquatic ecosystems and public health due to its high resistance to biodegradation and its ability to induce the development of antibiotic resistance genes (ARGs) in the aquatic environment. Given the inefficiency of conventional wastewater treatment plants (based on biological treatment) in removing these chemically stable compounds, the development of advanced and efficient treatment

technologies has become essential (Mazhandu and Mashifana, 2024; Eapen et al., 2024). The toxicity of pharmaceutical residues in aquatic systems, and the treatment routes available for their removal, have recently been reviewed in detail (Obaid et al., 2023).

In recent years, electrocoagulation (EC) processes have gained significant attention as a promising and environmentally friendly alternative for treating wastewater contaminated with complex organic compounds, due to their ease of operation, lack of need for external chemical additives, and high efficiency in sedimentation and surface adsorption. Its versatility is reflected in recent applications that range from the combined electrocoagulation and advanced oxidation

of refinery wastewater (Albrazanjy et al., 2024) to the continuous-flow treatment of oily wastewater (Elwakil et al., 2024). However, the main economic obstacle limiting the widespread industrial application of this technology lies in the continuous consumption and high cost of commercial metal electrodes (anodes), which contradicts the principles of sustainable development (Tahreen et al., 2020; Al-Qodah et al., 2025).

Based on the principles of green chemistry and the circular economy, the idea of recycling solid metal waste emerges as an innovative and dual-benefit solution. Empty tomato paste cans, which are made of mild steel and are referred to here as recycled mild steel (RMS), are a rich source of metal waste that can be recovered and turned into sustainable electrodes. The use of these alternative electrodes has a dual purpose: it not only reduces costs but also represents an effective strategy for solid waste removal and management, thus contributing to environmental protection (Alvim et al., 2025; Szymański et al., 2026).

Although numerous studies and literature have addressed the use of scrap metal as electrodes, a detailed comparative gap remains regarding the performance of CMS mild steel electrodes and RMS recycled mild steel from tomato paste cans, particularly when used to remove pharmaceutical waste such as amoxicillin residue from water. Furthermore, the physicochemical properties of these electrodes, related to surface interactions, kinetic models, and adsorption behaviors, require further investigation to explore the practical feasibility of the system (Bani-Melhem et al., 2023; Lefherz et al., 2025).

Therefore, the present study was designed to close this gap by comparing the two systems (CMS and RMS) for the removal of amoxicillin from wastewater in an electrochemical reactor, and by examining their operating conditions, namely the initial pH, the current, the initial pollutant concentration and the inter-electrode spacing.

In order to provide a comprehensive physical and chemical description of the surface process, the work specifically set out to (i) analyse the removal kinetics by applying the pseudo-first-order and pseudo-second-order models, so as to determine the reaction rates and to interpret the mass-transport mechanism of amoxicillin; (ii) describe the dependence of the amount adsorbed on the residual concentration at the end of the treatment period by fitting the data to the classical Langmuir and Freundlich models, so as to characterise

the nature of the surface reaction, the distribution of the amoxicillin molecules over the electro-generated floc and the apparent adsorption capacity ($q_{\max}$); and (iii) evaluate the electrochemical engineering and energetic performance of the two electrode materials.

The novelty of this work lies in presenting an applied model for converting metal packaging waste into functional electrodes for the treatment of water that is persistently contaminated with pharmaceutical residues, thereby indicating a possible route towards more sustainable water treatment technologies on a wider scale. The methodology adopted here also provides a basis for subsequent statistical optimisation approaches such as response surface methodology (RSM).

MATERIALS AND METHODS

Chemicals

In this study, active pharmaceutical ingredient (API) – pure amoxicillin, supplied by the Samarra Pharmaceutical Laboratory, was used both to construct the calibration curve for amoxicillin absorbance by ultraviolet (UV) spectrophotometry and in all experimental tests. Its chemical structure is shown in Figure 1.

The pH of the solution was adjusted using sodium hydroxide (NaOH) at a concentration of 1 M (99% purity) and sulfuric acid (H_2SO_4) at a concentration of 0.5 M (36%) obtained from local markets. Amoxicillin solutions were prepared by dissolving 10, 25, 50 or 100 mg of the active pharmaceutical ingredient in one litre of distilled water, giving initial concentrations of 10, 25, 50 and 100 mg/L. Each solution was mixed for 15 minutes before use.

Electrodes

Two types of electrodes were used:

- commercial mild steel (CMS) electrodes measuring $2.5 \times 3 \times 0.1$ cm,

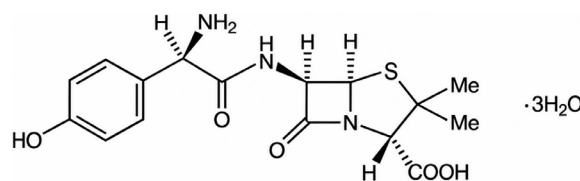


Figure 1. Chemical structure of amoxicillin (Al-Kadumi et al., 2019)

- recycled mild steel (RMS) electrodes recovered from empty tomato paste cans.

Flat sheets of recycled mild steel (RMS) were extracted from waste cans. Commercial mild steel (CMS) sheets of identical dimensions ($2.5 \times 3 \times 0.1$ cm) were used for electrochemical comparison. To ensure complete electrical conductivity and remove the insulating polymer coating (lacquer) lining the cans, the recycled iron sheets were heat-treated at 350 °C for 15 minutes, followed by fine mechanical sanding using silicon carbide sandpaper with a grit range of 240–1200 until a bright metallic surface was achieved. It was free of impurities. Before each operational test, both electrodes (commercial and recycled) were degreased by immersion in acetone for 10 minutes. The surface was then activated and stripped of oxides by immersion in a 10% by-volume hydrochloric acid solution for two minutes. Finally, the electrodes were thoroughly washed with deionized water and dried in a convection oven at 60 °C to ensure stable initial electrode weight before the electrochemical coagulation process began. The RMS electrode is shown in Figure 2 (Bani-Melhem and Al-Kilani, 2023).

Operating conditions

The electrochemical coagulation experiments were carried out in the reactor shown in Figure 3 inside a glass beaker containing aqueous amoxicillin solution, where the electrodes were immersed once (CMS) and a second time (RMS). It was connected to a DC power supply. To study and determine the optimal operating conditions for contaminant removal, a one-factor-at-a-time methodology was adopted to determine the ideal value to be used in the next step. The mixing

speed and room temperature were kept constant throughout the experiments, while the operating parameters of the electrodes were studied within the following range: initial pH (5.0, 7.0 and 8.0); initial amoxicillin concentration (10, 25, 50 and 100 mg/L); electrode spacing (1.0, 1.5, and 2.0 cm); applied voltage (5, 10, 15 and 20 V). Each operating experiment lasted a total of 90 minutes, during which six samples were taken periodically, one sample every 15 minutes (at 15, 30, 45, 60, 75 and 90 minutes). Sodium chloride (NaCl) was added at a concentration of 1 g/L as a supporting electrolyte solution. According to standard protocols, samples were collected periodically, stored in polyethylene containers, and analyzed by UV spectroscopy to determine the residual amoxicillin concentration and monitor its elimination kinetics, while simultaneously monitoring changes in pH and temperature over time. A single-beam spectrometer (SP-OPTIMA, Germany) was used for the spectroscopic analysis.

Spectrophotometric analysis and calibration curve

To determine the concentration of amoxicillin (AMX) in aqueous solutions, an SP-OPTIMA single-beam UV-Vis spectrophotometer (made in Germany) was used, with absorbance scans performed within the spectral range of 200 to 650 nm. The spectral results showed that the wavelength of maximum absorption (λ_{max}) of amoxicillin is 272 nm in a neutral medium. To meet the requirements of quantitative measurement and based on the Beer-Lambert Law, a standard calibration curve was constructed for amoxicillin over the range 0–150 mg/L, which brackets every initial concentration used in this work. Figure 4 shows the linear relationship between



Figure 2. Electrode materials: (a) commercial mild steel electrode, (b) tomato paste cans, (c) recycled mild steel electrode

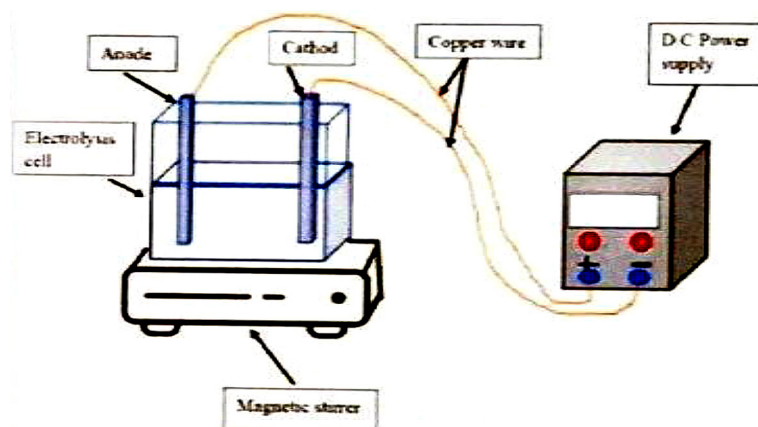


Figure 3. Schematic diagram of the electrochemical reactor

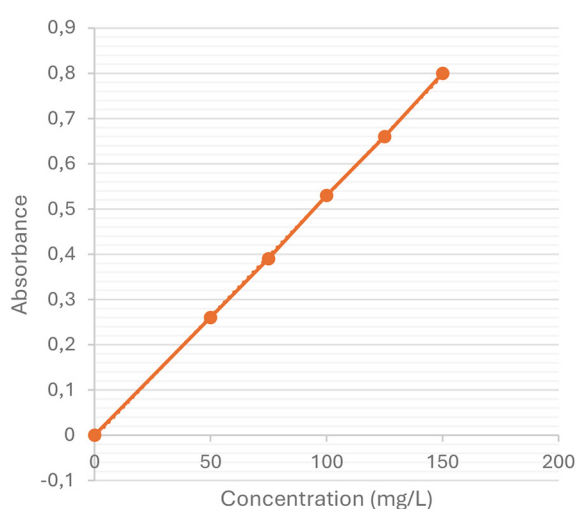


Figure 4. Calibration curve for amoxicillin

the measured absorbance and the corresponding concentration, described by $A = 0.005331C - 0.004286$ with a correlation coefficient of $R^2 = 0.9998$, which ensures the accuracy of the subsequent experimental measurements.

AMX removal efficiency (R) has been calculated using the following equation (Equation 1):

$$R (\%) = [(C_0 - C_t) / C_0] \times 100 \quad (1)$$

where: C_0 (mg/L) is the initial concentration of AMX in the solution, C_t (mg/L) is the concentration of AMX after t minutes, and R (%) is the removal efficiency of AMX.

Characterisation of the electrodes and flocs

To evaluate the physical properties of the two treatment systems (CMS and RMS), the samples were examined using scanning electron microscopy (SEM). SEM was used to characterize the topography of the electrode surfaces and to

observe structural changes, corrosion, and dissolution patterns resulting from the electrochemical reaction for both electrodes before and after the treatment process.

Kinetics and isotherm modelling

To analyze the mechanism and rate of amoxicillin (AMX) removal and its adsorption capacity on colloidal electrode surfaces (CMS and RMS), the following mathematical models were applied:

Kinetic models

Pseudo-first-order model: the removal rate is taken to be proportional to the residual contaminant concentration in solution (Al-Kindi and Al Haidari, 2021):

$$\ln(C_0 / C_t) = k_1 t \quad (2)$$

Pseudo-second-order model: chemisorption, through ion exchange or covalent bonding, is taken to be the rate-limiting step:

$$t / q_t = 1 / (k_2 q_e^2) + t / q_e \quad (3)$$

$$q_t = (C_0 - C_t) V / m \quad (4)$$

where: C_0 and C_t are the amoxicillin concentrations at time zero and at time t (mg/L); q_t and q_e are the amounts adsorbed per unit mass of electro-generated coagulant at time t and at the end of the 90-minute run (mg/g); k_1 (min^{-1}) and k_2 ($\text{g} \cdot \text{mg}^{-1} \cdot \text{min}^{-1}$) are the pseudo-first-order and pseudo-second-order rate constants; V is the treated volume (L); and m is the mass of coagulant generated (g). k_1 is obtained as the slope of $\ln(C_0/C_t)$ against t , while $1/q_e$ and $1/(k_2 q_e^2)$ are the slope and the intercept of t/q_t against t .

Adsorption isotherms

Langmuir model: adsorption is assumed to occur as a monolayer on a homogeneous surface with a finite maximum capacity (Al-Kindi and Alnasrawy, 2022):

$$C_e / q_e = 1 / (q_{max} K_L) + C_e / q_{max} \quad (5)$$

Freundlich model: adsorption is assumed to occur in multiple layers on an energetically heterogeneous surface (Sudiana et al., 2022):

$$\ln q_e = \ln K_F + (1/n) \ln C_e \quad (6)$$

where: C_e is the amoxicillin concentration remaining at the end of the 90-minute run (mg/L); q_e is the corresponding amount adsorbed (mg/g); q_{max} is the apparent monolayer capacity (mg/g); K_L (L/mg) and K_F ((mg/g)(L/mg)^{1/n}) are the Langmuir and Freundlich constants; and $1/n$ is the adsorption intensity index. The dimensionless separation factor is obtained as $R_L = 1/(1 + K_L C_0)$.

The kinetic constants were obtained from the full 90-minute concentration profile of each run. The isotherm points were taken as the residual concentration measured after 90 minutes in each of the four initial-concentration runs, which gives four independent operating points per electrode material. The residual concentration was still decreasing at that time, so these are fixed-time operating points rather than true equilibrium points, and the isotherm constants derived from them are reported as apparent values. The treated volume was $V = 1$ L, and the mass of coagulant m was obtained from Faraday's law, Equation 9, using the current measured at the operating voltage of these runs, 10 V: 0.89 A for the CMS electrode and 0.845 A for the RMS electrode, which over 90 minutes corresponds to 1.391 g and 1.321 g of dissolved iron respectively. Both q_t and q_e are therefore expressed per gram of iron released into the reactor.

RESULTS AND DISCUSSION

Electrode morphology and the effect of the electrochemical reaction

SEM was used to evaluate the structural changes to the surfaces of CMS electrodes resulting from anodic decomposition during

amoxicillin treatment. Figure 5a shows the initial state of the CMS electrode, characterized by a relatively smooth and homogeneous surface with some minor mechanical defects resulting from manufacturing, and completely free of any oxidation products. In contrast, the image recorded after electrocoagulation (Figure 5b) reveals a radical change in the surface topography of the CMS electrode; the surface smoothness has disappeared and been replaced by irregular protrusions and depressions due to severe electrochemical corrosion and iron ($\text{Fe}^{2+}/\text{Fe}^{3+}$) dissolution. A dense accumulation of insoluble deposits, consistent in appearance with iron hydroxides, was also observed on the used surface. These deposits are the coagulant generated in situ; the micrographs establish their presence and morphology, while the interaction with amoxicillin is inferred from the removal and isotherm data rather than from the images themselves. These structural morphological changes are consistent with the anode dissolution behavior described in the scientific literature for the generation of surface-active metal coagulants (Vasudevan et al., 2011; Auguste et al., 2016).

SEM images of the RMS electrode before and after electrochemical coagulation reveal, in Figure 6a, a cohesive, flat metallic substrate with circular microcavities/voids distributed across the surface. This distinctive morphological appearance is attributed to the double treatment the tomato paste can tin underwent. Furthermore, the heat treatment (350 °C) used to remove the insulating coating and tin, followed by mechanical sanding with silicon carbide, completely removes the surface, exposing the underlying steel layer and creating microscopic cavities. This structure increases the geometric roughness of the electrode surface. Whether it also increases the electrochemically active area was not determined here, since that would require an independent electrochemical measurement. After use (Figure 6b), that is, after the electrode had been subjected to electrocoagulation, the surface exhibits severe corrosion and deep structural degradation due to the accelerated anodic dissolution of iron ($\text{Fe}^{2+}/\text{Fe}^{3+}$). The initial surface features are completely obliterated, replaced by distinct micro-grooves that reveal intergranular corrosion of the metal under the influence of the applied electric current. Furthermore, a dense accumulation of light-coloured particles, consistent with the iron hydroxides generated in situ, is observed on the used surface. Taken together with the removal data, this indicates that

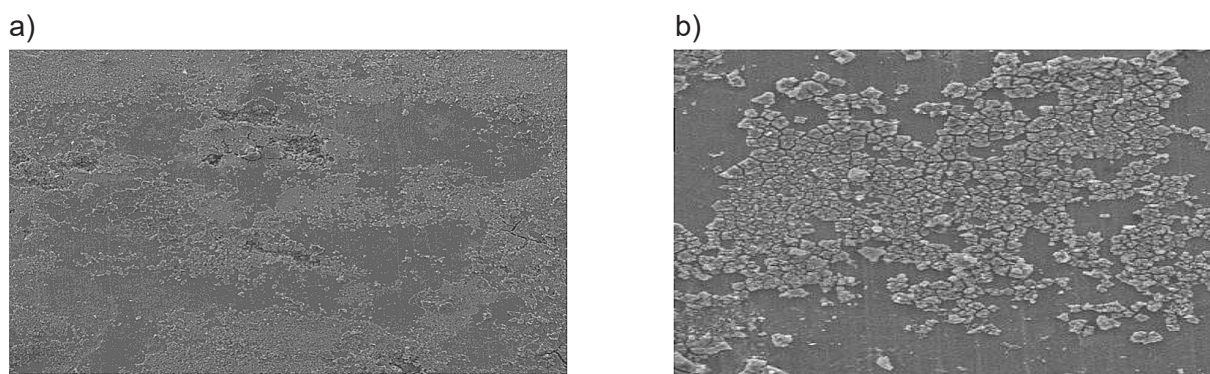


Figure 5. Surface morphology of the CMS electrode: (a) before use, (b) after use

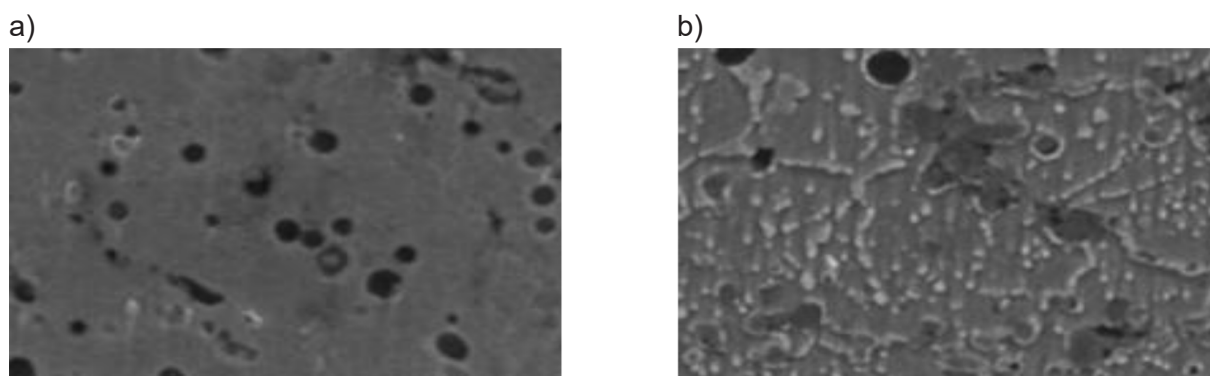


Figure 6. Surface morphology of the RMS electrode: (a) before use, (b) after use

the recycled electrode dissolves and generates coagulant in the same manner as the commercial material (Wang et al., 2025).

Effect of the operating parameters

Effect of the initial pH and the comparative removal mechanism

The experiment was conducted at a constant initial concentration of 50 mg/L, a voltage of 10 V, and a distance of 1.5 cm, with NaCl used as the electrolyte. The pH was varied (5, 7, and 8). Initial pH is one of the most important operational variables affecting electrochemical coagulation processes due to its dual role in determining the nature of the surface charges of the generated metal hydroxides and controlling the degree of ionization of the target pollutant particles in the solution. The research evaluates the removal efficiency behavior of amoxicillin at three different pH values (pH = 5.0, 7.0, and 8.0) by comparing commercially available mild steel (CMS) electrodes with their recycled counterparts from sealed containers (RMS). The CMS electrode recorded a maximum removal efficiency of 92%,

while the RMS electrode achieved a very similar efficiency of 88% under optimal conditions. At an acidic value (pH = 5), a relative decrease in the removal efficiency of both electrodes was observed. This is scientifically attributed to the dissolution of iron products and their transformation into fully soluble ions such as Fe^{2+} and Fe^{3+} , without allowing the formation of solid, surface-active polymeric hydroxide products necessary for coagulation and pollutant retention, in addition to the electrical repulsion between the positive surface and the ionized drug molecules (Weiss et al., 2021). In contrast, upon transitioning to a neutral medium (pH = 7.0), the removal efficiency jumped to its peak, reaching 92% for CMS and 88% for RMS. This high efficiency is explained by the rapid hydrolysis of iron ions and their immediate transformation into green and brown colloidal masses of ferrous and ferric hydroxides $\text{Fe}(\text{OH})_2$ and $\text{Fe}(\text{OH})_3$, which possess a huge surface area and neutral or slightly positive electrical charges that increase the efficiency of adsorption and retention of amoxicillin molecules via co-precipitation and charge neutralization mechanisms (Zhao et al., 2025). However, upon transitioning to an alkaline medium (pH = 8.0),

a slight decrease in performance was observed due to the formation of soluble negative iron ions such as $\text{Fe}(\text{OH})_4^-$, which are electrically repulsive to the negatively charged amoxicillin molecules in the alkaline medium (due to the ionization of the carboxyl groups in the drug molecule), thus hindering their approach to the formed flocculant (DorMohammadi et al., 2019). These very similar results for the two electrodes (92% versus 88%) demonstrate the success of the RMS electrode made from damaged tomato paste cans. The difference of four percentage points is within the resolution of these single determinations, which indicates that the recycled material can process emerging pharmaceutical contaminants as effectively as commercial mild steel under the conditions tested. Figures 7 and 8 show the residual amoxicillin concentration and the removal efficiency as a function of treatment time at the three initial pH values.

Effect of the initial concentration on the amoxicillin removal efficiency

To evaluate the capacity and efficiency of the electrochemical reactor in treating amoxicillin, it is essential to study the effect of the initial concentration of contaminants, as this is a crucial variable under different operating conditions. The experiments were conducted under the following conditions: an applied voltage of 10 V, pH 7.0, a distance between electrodes of 1.5 cm, and sodium chloride (NaCl) as the supporting electrolyte. The initial concentration of amoxicillin was

varied over 10, 25, 50 and 100 mg/L for the CMS and RMS electrodes. The results showed that the electrocoagulation system reached its highest removal efficiency at the lowest initial concentration, 10 mg/L, where the two electrodes performed almost identically: 96.5% for the RMS electrode and 97% for the CMS electrode. Efficiency then fell steadily with increasing load, to 94.8% and 95% at 25 mg/L, 93.9% and 94% at 50 mg/L, and 83% and 83.5% at 100 mg/L. This is attributed to the formation of stable iron hydroxide flocs at 10 V. The amount of flocs formed was sufficient to capture and retain all the amoxicillin molecules present in the solution, thus successfully removing them. Regarding the processing engineering and reaction kinetics perspective, it appears that this behavior is a result of the ratio of active sites available on the surfaces of iron flake particles to the number of pollutant particles at low concentrations, which reduces the resistance to mass transfer and the retardation forces, and accelerates the co-precipitation process. As the contaminant concentration gradually increases, the removal efficiency begins to decrease due to the saturation of the floc adsorption sites. The amount of floc becomes a limiting factor for the overall reaction rate, compared to the high abundance of drug molecules (Al Kindi and Al-Haidri, 2023). The sustainable RMS electrode achieving a removal efficiency of 96.5%, nearly matching that of a commercial electrode (97%), indicates that an electrode manufactured from food-can waste is practically feasible under these conditions. This indicates that the pre-treatment of the RMS

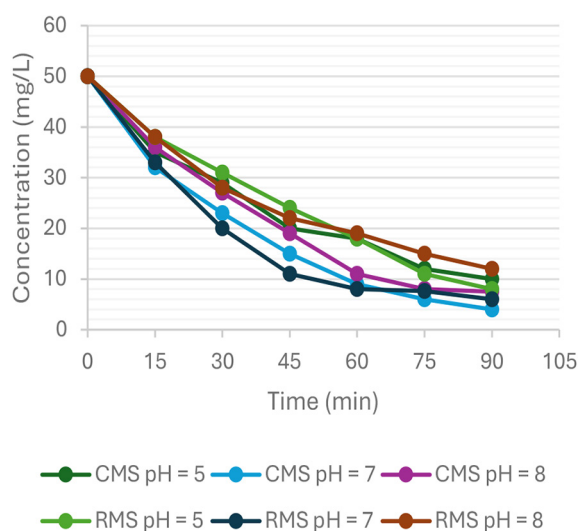


Figure 7. Residual amoxicillin concentration at different initial pH values

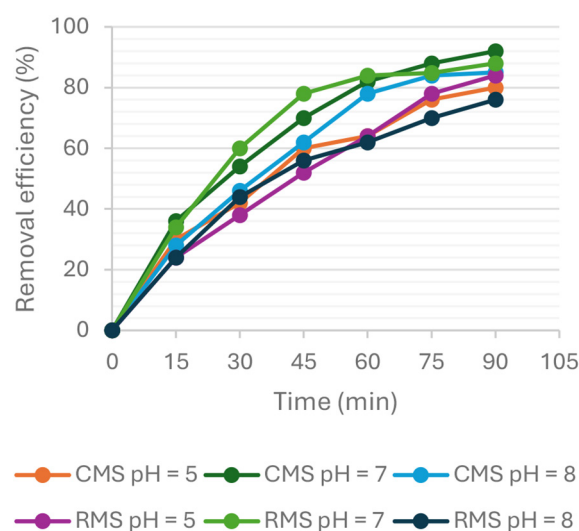


Figure 8. Amoxicillin removal efficiency at different initial pH values

electrode succeeded in providing active sites for anodic dissolution comparable to those of commercial iron, opening up promising prospects for the use of recycled materials in the treatment of antibiotic-contaminated water. Figures 9 and 10 show the residual amoxicillin concentration and the removal efficiency as a function of treatment time at the four initial amoxicillin concentrations.

Effect of the inter-electrode distance on the ion transport mechanism

The inter-electrode distance is a critical operational parameter in the design of electrochemical reactors due to its direct impact on the ohmic resistance of the solution, energy consumption, and mass transport. Experiments were conducted under constant conditions (pH = 7.0, voltage 10 V, initial amoxicillin concentration 25 mg/L, and using sodium chloride (NaCl) as the supporting electrolyte), with varying inter-electrode distances of 1.0, 1.5, and 2.0 cm for both systems (CMS and RMS). The results showed that the optimal distance between the electrodes is 1 cm, which provides the best operational efficiency. The highest amoxicillin removal efficiency reached 98.3% for the CMS electrode, while it was 98.1% for the RMS electrode. This is due to both engineering and physical reasons. Reducing the distance between the anode and cathode leads to a decrease in the ohmic resistance of the solution, according to Ohm's law. This, in turn, reduces the potential difference, which decreases ion movement

and increases the effective cell current density at 10 V. Consequently, the dissolution of iron at the anode increases and accelerates, leading to increased formation of iron hydroxide at the site. As a result, contaminants and associated precipitates are deposited and retained. This contrasts with what happens when the distance between the electrodes increases to 1.5–2 cm. The ohmic resistance of the cell increases, causing a loss of potential due to the reduced potential difference. This impedes ion movement, thus reducing the amount of precipitate formed over time. As a result, the overall removal efficiency decreases and energy consumption increases (Almalki, 2024). A shorter distance between electrodes is mechanically shorter, increasing the likelihood of amoxicillin molecules colliding with iron hydroxide agglomerates, thus accelerating surface adsorption kinetics. The highest efficiency, 98.3% for the CMS electrode and 98.1% for the RMS electrode, indicates that the RMS electrode responds hydrodynamically and electrochemically in a manner comparable to the CMS electrode under different reactor geometries. This result demonstrates the similarity to the high efficiency of the RMS electrode in homogeneous solubility and the absence of energy losses, making it a viable alternative in integrated electrochemical reactors. Figures 11 and 12 show the influence of the inter-electrode distance on the residual amoxicillin concentration and on the removal efficiency.

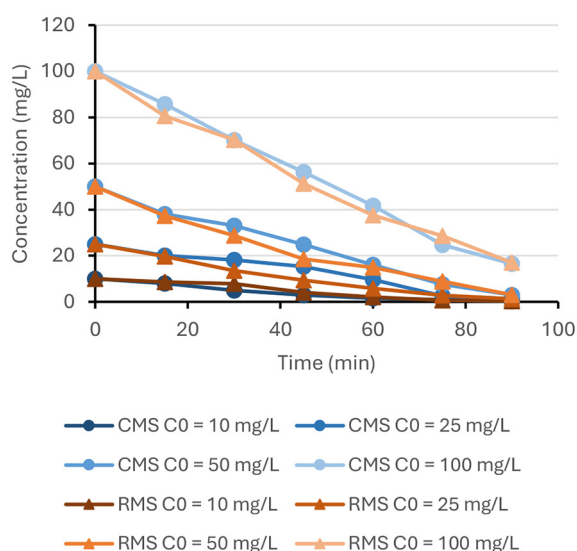


Figure 9. Effect of the initial amoxicillin concentration on the residual amoxicillin concentration in the electrochemical reactor

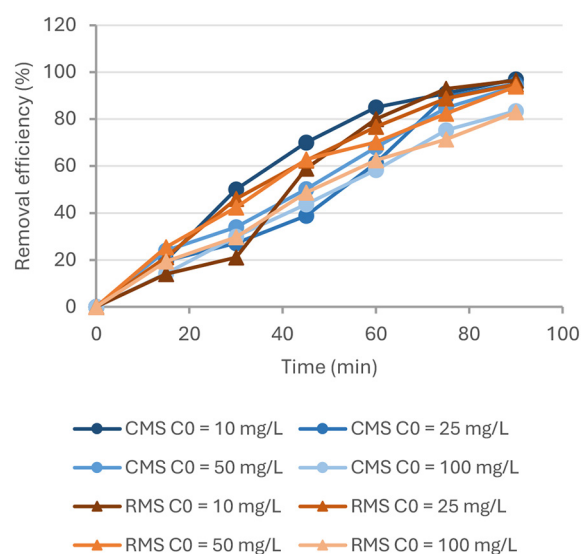


Figure 10. Effect of the initial amoxicillin concentration on the removal efficiency in the electrochemical reactor

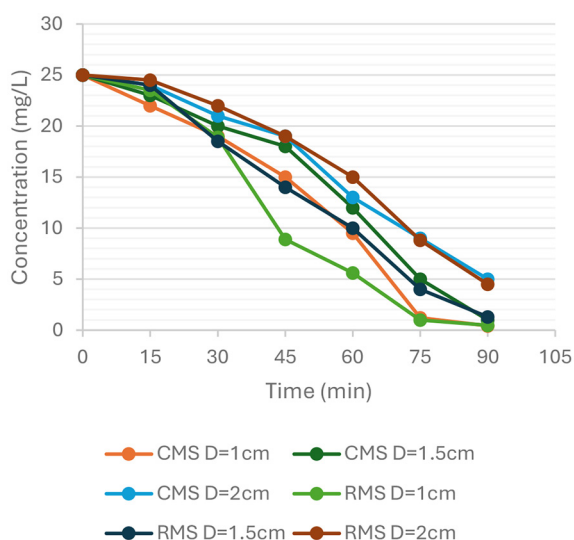


Figure 11. Effect of the electrode spacing on the residual amoxicillin concentration for the CMS and RMS electrodes

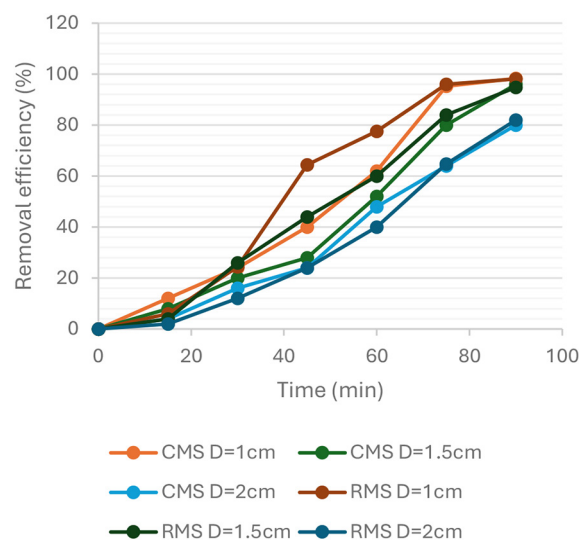


Figure 12. Effect of the electrode spacing on the removal efficiency for the CMS and RMS electrodes

Effect of the applied voltage and the current density

The driving force of the electrochemical coagulation process and the main dynamic applied potential directly control the electron flux density and current flow rate within the reactor. Based on Faraday's law, the size of the colloidal active iron hydroxide nuclei generated on-site is determined. To determine this dynamic, experiments were conducted under operating conditions of an initial amoxicillin concentration of 25 mg/L, pH = 7.0, electrode spacing of 1.0 cm, and the use of sodium chloride as a supporting electrolyte. The voltage was varied each time at operating levels (5, 10, 15, and 20 V) for both systems (CMS and RMS). The system showed a clear ohmic response when the voltage increased at a constant spacing, which occurred at a high increase in current intensity. The RMS electrode recorded current values of 0.456, 0.845, 1.425, and 2.389 A, while the CMS electrode achieved almost similar values of 0.48, 0.89, 1.45, and 2.44 A for the applied voltage values, respectively. The results showed a strong positive correlation between voltage stimulation and increased efficiency of drug compound processing up to optimal operating values at 15 V (equivalent to a current of 1.425 A for the RMS electrode and 1.45 A for the CMS electrode). The removal efficiency reached its highest value of 99.4% for the RMS electrode and 99.3% for the CMS electrode as a result of the noticeable improvement in performance in the

(5–15 V) range to doubling the effective charge, accelerating the movement of electrons, which led to increasing the rate of iron dissolution at the anode to the maximum and forming a wide and dense network of $\text{Fe}(\text{OH})_2/\text{Fe}(\text{OH})_3$ colloidal material that has the ability to trap and deposit contaminants (Syaichurrozi et al., 2020). This abundance contributes to increased collision and chemical binding opportunities with amoxicillin molecules, thus enhancing the co-precipitation mechanism and achieving near-complete charge neutralization. On the other hand, it was observed that when the voltage was raised further to 20 V (accompanied by a high current of 2.44 A), the removal efficiency no longer improved and in fact fell slightly, to 97.6% for the CMS electrode and 98.98% for the RMS electrode. This behavior is geometrically explained by the phenomenon of system saturation, where the amount of coagulants generated exceeds the amount of pollutant molecules available in the solution (25 mg/L). Furthermore, high voltages and high currents lead to increased parallel hydrolysis and dense gas (H_2) bubble generation at the cathode. This can cause mechanical dispersal of the resulting flocculant (flakes breakage) instead of their deposition, as well as an unjustified increase in electrical energy consumption without any corresponding improvement in treatment efficiency. Under the optimal operating conditions the two materials performed identically within the resolution of the measurement: 99.4% for the RMS electrode at 15 V and 1.425 A, and 99.3% for the CMS electrode

at 15 V and 1.45 A. A difference of one tenth of a percentage point between single runs carries no statistical weight, so the two electrodes are treated here as equivalent rather than ranked. That equivalence is itself the significant result, because it is obtained with a material recovered from food packaging. It also indicates that the two electrodes presented a comparable current response to the cell under the operating conditions tested, which is consistent with their morphological characteristics before use as revealed by SEM. The scars, cavities and surface roughness produced by the heat and mechanical treatment of the food cans give the RMS electrode a visibly rougher surface than the commercial CMS electrode. Scanning electron microscopy establishes this morphology but cannot quantify the electrochemically active area, so the roughness is reported here as an observation rather than as a measured increase in active surface. These results support the potential of the RMS electrode as a more sustainable alternative for the treatment of pharmaceutical waste. No costing of the recycled electrodes was carried out in this work: the collection, cutting, thermal and mechanical pre-treatment and cleaning of the food-can sheets all represent inputs that would have to be quantified before any economic claim could be made. Figures 13 and 14 show the amoxicillin removal as a function of the applied voltage and of the treatment time. A surface rich in structural defects may in principle offer a greater number of electrochemically active sites, and both electrode material and surface area

are known to influence electrochemical performance (Naseri et al., 2022). No electrochemical impedance spectroscopy was carried out in this work, however, so no claim is made here about the charge-transfer resistance of either material; the currents drawn at 15 V differed by less than 2% (1.425 A for RMS against 1.45 A for CMS), which does not indicate a substantial difference in interfacial resistance in either direction.

Electrochemical engineering and energetic evaluation

The electrochemical engineering and energetic performance of the two systems was evaluated using the following equations.

The current density (CD) equation is used to calculate the current applied per unit area of the immersed electrode surface, which is the primary indicator of the intensity of the electrochemical reaction (Popov et al., 2011):

$$CD = I / A \quad (7)$$

where: CD – current density (mA/cm^2); I – actual current read from the power supply (A); A – effective immersed surface area of the electrode, both sides together (cm^2).

The law of electrical energy consumption (EC) calculates the electrical energy consumed per cubic metre (m^3) of treated water in order to quantify the energy demand of the reactor using the following equation (Hamawand, 2023):

$$EC = (V I t) / (1000 \text{ v}) \quad (8)$$

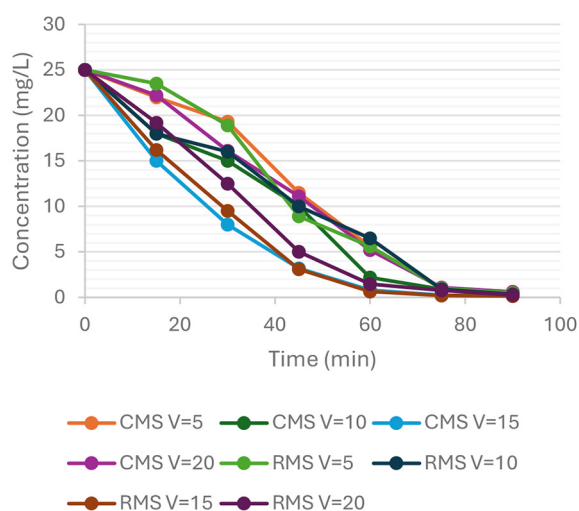


Figure 13. Effect of the applied voltage on the residual amoxicillin concentration in the electrochemical reactor

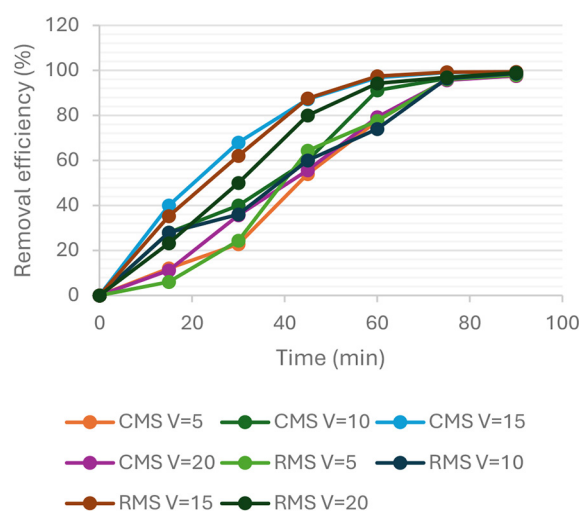


Figure 14. Effect of the applied voltage on the removal efficiency in the electrochemical reactor

where: EC – electrical energy consumption (kWh/m^3); V – applied voltage (V); I – actual current (A); t – reactor operating time (h); v – volume of solution treated in the reactor (m^3), noting that $1\text{ L} = 0.001\text{ m}^3$.

Faraday's law of electrode consumption is used to calculate the theoretical mass lost (dissolved) from an iron anode as a result of electrochemical oxidation and coagulation (Liu et al., 2024):

$$\Delta m = (I t M) / (z F) \quad (9)$$

where: Δm – mass of iron dissolved from the anode (g); I – actual electric current (A); t – duration of the electrochemical reaction (s); M – molar mass of iron ($M = 55.845\text{ g/mol}$); z – valence of the iron ions produced by anodic dissolution ($z = 2$ for ferrous ions, Fe^{2+}); F – Faraday constant ($F = 96485\text{ C/mol}$).

The applied voltage is the primary driving force in electrochemical coagulation systems. Furthermore, the applied voltage directly regulates the current density, which in turn determines the anodic dissolution rate and the amount of active metal hydroxides generated within the reactor, according to Faraday's law of electrolysis. To confirm the dynamic response, a series of experiments were conducted at voltages of 5, 10, 15, and 20 V for both CMS and RMS electrode systems, under standard operating conditions: a 1.0 cm electrode spacing, a neutral pH ($\text{pH} = 7.0$), the addition of 1.0 g/L sodium chloride (NaCl) as a coordinating electrolyte, and an initial amoxicillin concentration of 25 mg/L. The results showed a strong correlation between the amoxicillin

removal efficiency and the applied voltage, reaching its highest efficiency of 99.4% for the RMS electrode and 99.3% for the CMS electrode at 15 V. From the perspective of electrochemistry and hydrodynamics, raising the voltage from 5 to 15 volts resulted in a significant increase in the actual current from 0.456 to 1.425 amps for the RMS system and from 0.48 to 1.45 amps for the CMS system. This demonstrates the close correlation between the total ohmic resistance of the reactor and the surface electrical conductivity behavior of both electrodes, which reflected this similarity in current levels. Table 1 gives the calculated engineering and energetic indicators under the optimal operating conditions. Because the removal efficiencies reported above were reached only after 90 minutes, the energy consumption and the Faradaic mass loss are listed both at 15 minutes and at the 90-minute end point, and it is the 90-minute values that correspond to the reported removal. The specific energy demand of 32.63 kWh/m^3 for the CMS electrode and 32.06 kWh/m^3 for the RMS electrode reflects a one-litre bench cell driven at a high current density over an immersed area of 15 cm^2 , and is not directly transferable to a reactor designed for scale; expressed per unit of amoxicillin removed it corresponds to 1.31 and 1.29 kWh/g respectively.

The near-perfect removal efficiency at current densities of 96.67 mA/cm^2 (CMS) and 95.00 mA/cm^2 (RMS) is attributed to the accelerated kinetic oxidation of iron at the anode and the generation of massive colloidal masses of ferrous and ferric hydroxides $[\text{Fe}(\text{OH})_2/\text{Fe}(\text{OH})_3]$, which enhances the mechanisms of charge neutralization and co-precipitation. In contrast, applying higher voltages (20 V) accompanied by higher currents

Table 1. Electrochemical and energetic indicators of the CMS and RMS electrodes under the optimal operating conditions (15 V, 1.0 cm electrode spacing, pH 7, $C_0 = 25\text{ mg/L}$, immersed area $A = 15\text{ cm}^2$, treated volume 1 L)

Indicator	CMS electrode	RMS electrode	Interpretation
Actual current, I (A)	1.45	1.425	Comparable current response under the conditions tested.
Current density, CD (mA/cm^2)	96.67	95.00	Comparable ion flux over the immersed area.
Removal after 15 min (%)	40.0	35.2	Treatment far from complete at this point.
Removal after 90 min (%)	99.3	99.4	The reported optimum; the two materials are indistinguishable.
EC after 15 min (kWh/m^3)	5.44	5.34	Energy drawn to reach the partial removal above.
EC after 90 min (kWh/m^3)	32.63	32.06	Energy drawn to reach the reported removal.
Δm after 15 min (g)	0.378	0.371	Coagulant generated at the intermediate point.
Δm after 90 min (g)	2.266	2.227	Practically equivalent masses of coagulant.
Energy per g removed, 90 min (kWh/g)	1.31	1.29	Bench-scale value; not transferable to a scaled reactor.

(2.44 A for CMS and 2.389 A for RMS) stabilized the processing efficiency without any significant increase. As a result of the saturation of the active flocculation sites and the generation of dense hydrogen (H_2) gas bubbles at the cathode, the resulting hydrodynamic-mechanical dispersion of the formed flocculations led to an unjustified increase in energy consumption (Mashale et al., 2025). The equivalence of the two materials, 99.4% for RMS against 99.3% for CMS, is consistent with the morphological and topographical characteristics of their surfaces as revealed by scanning electron microscopy (SEM). The recycled electrode drew a slightly lower current and current density than the commercial one, a difference of less than 2% that lies within the resolution of these single determinations. The smoothing and heat treatment of the tomato paste cans resulted in a surface with fine topography but numerous cavities and scars, and a very rough surface. These defects give the recycled surface a greater geometric area of contact with the electrolyte than the smooth commercial surface. Whether this corresponds to a larger electrochemically active area, or to a lower charge-transfer resistance, was not determined, since electrochemical impedance spectroscopy and active-area measurements were outside the scope of this work. What the data do establish is that the two materials drew comparable currents, dissolved at comparable rates according to Faraday's law, and achieved comparable removal of amoxicillin. Over the full 90-minute treatment the RMS electrode drew marginally less specific energy than the CMS system, 32.06 kWh/m³ against 32.63 kWh/m³, a difference of under two per cent that again lies within the resolution of single runs. This supports the engineering feasibility of

converting waste metal into functional electrodes for the treatment of emerging pharmaceutical pollutants, and hence the potential sustainability benefit of doing so.

Kinetics and isotherm modelling

Kinetic analysis showed that the removal of amoxicillin during electrocoagulation follows pseudo-first-order behaviour on both electrode materials. Plots of $\ln(C_0/C_t)$ against time were linear at every initial concentration examined, with correlation coefficients between 0.849 and 0.966 for the CMS electrode and between 0.924 and 0.972 for the RMS electrode. The apparent rate constant decreased steadily as the initial concentration increased, from 0.0383 to 0.0200 min⁻¹ for CMS and from 0.0392 to 0.0191 min⁻¹ for RMS between 10 and 100 mg/L. This is the behaviour expected when a fixed quantity of electro-generated floc has to serve a growing number of pollutant molecules, so that the availability of active sites rather than the supply of amoxicillin governs the rate. The pseudo-second-order model was also tested. Plots of t/q_t against time were not linear at any concentration, giving correlation coefficients between 0.001 and 0.965, and the capacities it predicts depart from the measured values by up to two orders of magnitude, several of them being negative. The model is therefore not supported by the present data, and its rate constants and predicted capacities are not reported; Table 2 gives the correlation coefficient of each model so that the two can be compared directly. The reason is visible in the concentration profiles themselves: at 90 minutes the residual concentration was still falling steeply in every run, so

Table 2. Measured capacity, pseudo-first-order rate constants and the correlation coefficients of both kinetic models for the CMS and RMS electrodes at four initial amoxicillin concentrations

C_0 (mg/L)	$q_{e,exp}$ (mg/g)	k_1 (min ⁻¹)	R^2 , pseudo-first-order	R^2 , pseudo-second-order
Commercial mild steel (CMS)				
10	6.97	0.0383	0.9654	0.5191
25	17.08	0.0327	0.8485	0.0007
50	33.79	0.0295	0.9064	0.5795
100	60.04	0.0200	0.9557	0.0214
Recycled mild steel (RMS)				
10	7.31	0.0392	0.9237	0.2787
25	17.95	0.0324	0.9615	0.8424
50	35.55	0.0284	0.9305	0.9649
100	62.85	0.0191	0.9716	0.6754

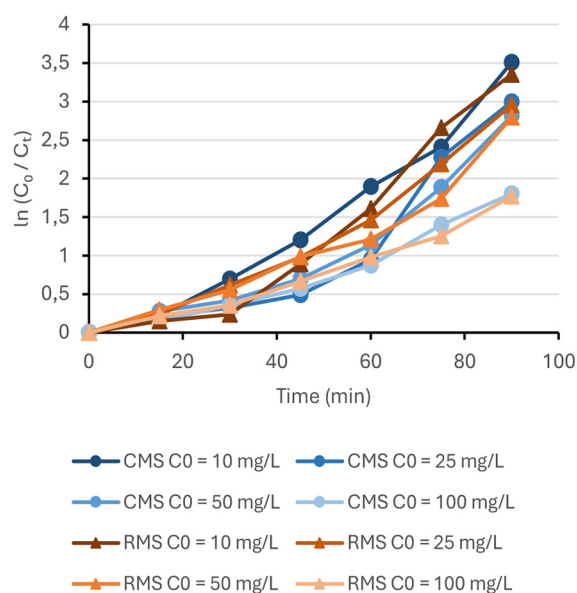


Figure 15. Pseudo-first-order kinetic model of amoxicillin removal on the CMS and RMS electrodes

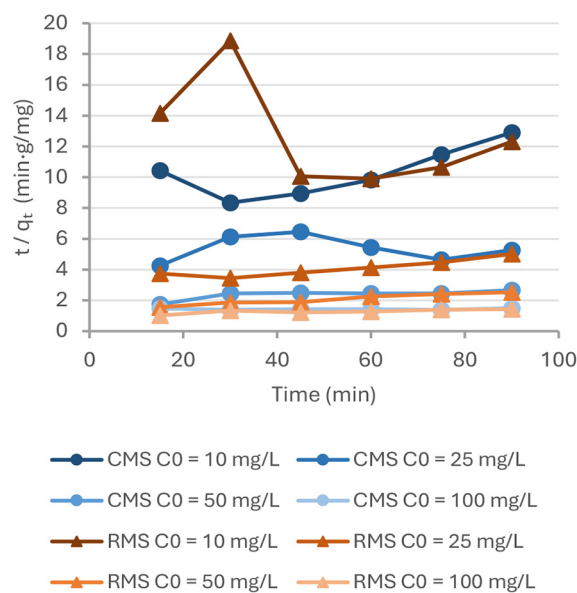


Figure 16. Pseudo-second-order kinetic model of amoxicillin removal on the CMS and RMS electrodes

none of the systems had reached the plateau that the pseudo-second-order linearisation assumes. Amoxicillin removal by electrocoagulation has previously been optimised by response surface methodology (Alidadi et al., 2018). The results of the pseudo-first-order and pseudo-second-order linearisations are shown in Figures 15 and 16, while Table 2 lists the corresponding constants.

The isotherm data were obtained by taking the residual concentration at 90 minutes from each of the four initial-concentration runs, so that every isotherm rests on four independent operating points. Because the residual concentration was still falling at 90 minutes, these are fixed-time operating isotherms rather than equilibrium isotherms, and the capacities derived from them are lower bounds on the values that would be reached at true equilibrium. On this basis the Langmuir model describes the process better than

the Freundlich model for both electrode materials, with correlation coefficients of 0.9956 for the CMS electrode and 0.9974 for the RMS electrode, against 0.9700 and 0.9617 for the corresponding Freundlich fits. The apparent monolayer capacity ($q_{\max}$) was 72.3 mg/g for the CMS electrode and 76.5 mg/g for the RMS electrode, expressed per gram of iron released into the reactor, and the Langmuir constant (K_L) was 0.293 and 0.271 L/mg respectively. The separation factor (R_L) fell from 0.254 to 0.033 for CMS and from 0.269 to 0.036 for RMS as the initial concentration rose from 10 to 100 mg/L, lying in every case between 0 and 1 and confirming that the adsorption is favourable. The Freundlich exponent n was 1.84 for CMS and 1.79 for RMS, both inside the $1 < n < 10$ band that also indicates favourable adsorption, although the lower correlation coefficients show only that the monolayer form of the model

Table 3. Langmuir and Freundlich isotherm constants for the CMS and RMS electrodes, obtained from the 90-minute operating points of the four initial-concentration runs

Isotherm	Constant	CMS electrode	RMS electrode
Langmuir	$q_{\max}$, apparent (mg/g)	72.3	76.5
	K_L (L/mg)	0.2931	0.2713
	R_L ($C_0 = 10\text{--}100$ mg/L)	0.254–0.033	0.269–0.036
	R^2	0.9956	0.9974
Freundlich	K_F (mg/g)(L/mg) $^{(1/n)}$	14.90	14.97
	n	1.837	1.791
	R^2	0.9700	0.9617

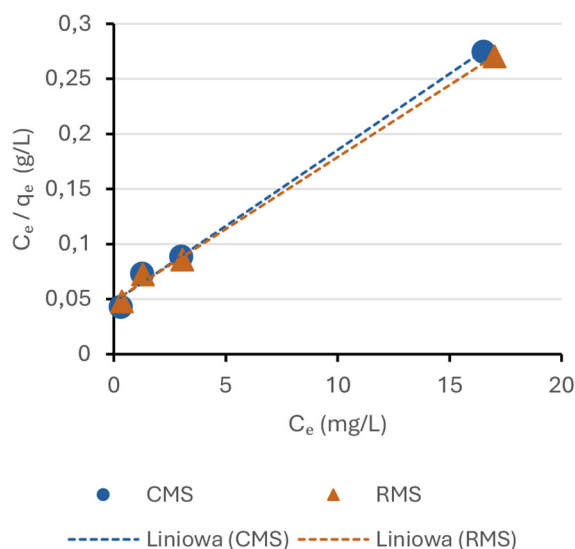


Figure 17. Langmuir isotherm for the electrochemical removal of amoxicillin on the CMS and RMS electrodes

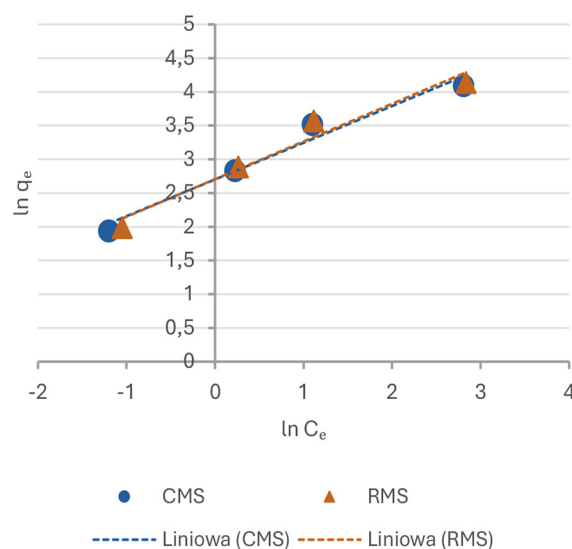


Figure 18. Freundlich isotherm for the electrochemical removal of amoxicillin on the CMS and RMS electrodes

describes these data better than the multilayer form. The recycled electrode reaches a slightly higher capacity per gram of coagulant, 76.5 against 72.3 mg/g, because it draws a marginally lower current and therefore releases less iron while removing the same amount of amoxicillin. The difference is small and rests on single runs, so it is reported as an indication that the pre-treated food-can steel generates a coagulant of at least equivalent quality rather than as a demonstration of superiority. These results are consistent with those reported by Touijer et al. (2023). Figures 17 and 18 show the Langmuir and Freundlich isotherms for the electrochemical removal of amoxicillin on the CMS and RMS electrodes, and Table 3 lists the corresponding isotherm constants.

CONCLUSIONS

Electrocoagulation demonstrated high efficiency in amoxicillin removal using both CMS electrodes and RMS electrodes, exceeding 99% removal efficiency under optimal operating conditions. These conditions—a 1 cm electrode spacing, 15 V power supply, and a pH of 7—resulted in high efficiency with reasonable energy consumption. The two electrode materials performed equivalently within the resolution of the measurements, which supports the potential of steel recovered from food packaging as an alternative to commercial mild steel in electrocoagulation under the conditions tested.

The kinetics study revealed that amoxicillin removal followed pseudo-first-order behaviour on both electrode materials, the apparent rate constant decreasing as the initial concentration increased. Adsorption modelling of the 90-minute data showed that the Langmuir isotherm was the most effective for describing amoxicillin removal by electrocoagulation, with an apparent monolayer capacity of 76.5 mg/g on the recycled electrode against 72.3 mg/g on the commercial one; because equilibrium had not been reached at that time, these capacities are lower bounds. This is a statement about which model better describes the shape of the fitted relationship, and is not by itself evidence that the electro-generated floc surface is energetically homogeneous. Electrodes recycled from tomato paste cans therefore combine the reuse of a discarded material with the simultaneous management of pharmaceutical and solid waste, which contributes to sustainable development and supports the circular economy. Throughout this work, removal denotes the transfer of amoxicillin from the aqueous phase into the iron hydroxide floc; degradation and mineralisation were not measured, and the amoxicillin-bearing sludge therefore requires further management.

Acknowledgements

The authors are grateful to the College of Civil Engineering, University of Technology – Iraq, for the laboratory facilities made available for this work.

REFERENCES

- Albrazanjy, M. G., Hasan, M. M., Al-Jadir, T., Kadhim, W. A., Ab. Rahim, M. H., Al-Rubaiey, N. A. (2024). Efficient and sustainable remediation of refinery wastewater using electrocoagulation and advanced oxidation techniques. *Ecological Engineering & Environmental Technology*, 25(3), 197–210. <https://doi.org/10.12912/27197050/178335>
- Alidadi, H., Ghorbanian, A., Ghorbanian, M., Rahmanzadeh, E., Nemanifar, N., Mehrabpour, M. (2018). Evaluation of amoxicillin antibiotic removal by electrocoagulation process from aqueous solutions: Optimization through response surface methodology. *Desalination and Water Treatment*, 132, 350–358. <https://doi.org/10.5004/dwt.2018.23159>
- Al-Kadumi, A. S., Fadhel, S. R., Ahmed, M. A., Musa, L. A. (2019). Colorimetric determination of amoxicillin in pure and some pharmaceutical formulations via reaction with potassium permanganate as oxidant reagent. *International Journal of Pharmaceutical Quality Assurance*, 10(2), 222–228. <https://doi.org/10.25258/ijpqa.10.2.2>
- Al-Kindi, G. Y., Al Haidari, H. A. (2021). The removal of ibuprofen drugs residues from municipal wastewater by Moringa oleifera seeds. *Journal of Ecological Engineering*, 22(1), 83–94. <https://doi.org/10.12911/22998993/128868>
- Al-Kindi, G. Y., Alnasrawy, S. T. (2022). Tetracycline remove from synthetic wastewater by using several methods. *Journal of Ecological Engineering*, 23(5), 137–148. <https://doi.org/10.12911/22998993/146999>
- Al Kindi, G. Y., Al-Haidri, H. A. (2023). Removal of pharmaceutical residues in 2D and 3D electrochemical processes by using orange peels. *Innovative Infrastructure Solutions*, 8(6), 171. <https://doi.org/10.1007/s41062-023-01142-5>
- Almalki, H. A. (2024). *Electrochemical dissolution of Fe in concentrated aqueous electrolyte* [Doctoral dissertation, University College London]. UCL Discovery. <https://discovery.ucl.ac.uk/id/eprint/10200853>
- Al-Qodah, Z., AL-Rajabi, M. M., Al Amayreh, H. H., Assirey, E., Bani-Melhem, K., Al-Shannag, M. (2025). Performance of continuous electrocoagulation processes (CEPs) as an efficient approach for the treatment of industrial organic pollutants: A comprehensive review. *Water*, 17(15), 2351. <https://doi.org/10.3390/w17152351>
- Alvim, D. S., Flor, G. de A., Teixeira, V. G., Suski, C. A., Kasemodel, M. C., D'Amelio, M. T. S., Alcântara, M. A. K. de. (2025). Aluminum recycling and its contribution to socio-environmental sustainability: A perspective from circular economy and environmental management. *Revista de Gestão Social e Ambiental*, 19(10), e013608. <https://doi.org/10.24857/rgsa.v19n10-041>
- Auguste, A. F. T., Quand-Meme, G. C., Ollo, K., Mohamed, B., Sahi Placide, S., Ibrahima, S., Lassiné, O. (2016). Electrochemical oxidation of amoxicillin in its commercial formulation on thermally prepared RuO₂/Ti. *Journal of Electrochemical Science and Technology*, 7(1), 82–89. <https://doi.org/10.5229/JECST.2016.7.1.82>
- Bani-Melhem, K., Al-Kilani, M. R. (2023). A comparison between iron and mild steel electrodes for the treatment of highly loaded grey water using an electrocoagulation technique. *Arabian Journal of Chemistry*, 16(10), 105199. <https://doi.org/10.1016/j.arabjc.2023.105199>
- Bani-Melhem, K., Al-Kilani, M. R., Tawalbeh, M. (2023). Evaluation of scrap metallic waste electrode materials for the application in electrocoagulation treatment of wastewater. *Chemosphere*, 310, 136668. <https://doi.org/10.1016/j.chemosphere.2022.136668>
- DorMohammadi, H., Pang, Q., Murkute, P., Árnadóttir, L., Burkan Isgor, O. (2019). Investigation of iron passivity in highly alkaline media using reactive-force field molecular dynamics. *Corrosion Science*, 157, 31–40. <https://doi.org/10.1016/j.corsci.2019.05.016>
- Eapen, J. V., Thomas, S., Antony, S., George, P., Antony, J. (2024). A review of the effects of pharmaceutical pollutants on humans and aquatic ecosystem. *Exploration of Drug Science*, 2, 484–507. <https://doi.org/10.37349/eds.2024.00058>
- Elwakil, A., El-Sayed, A.-E., Ayoub, M., El-Morsy, A. (2024). Efficiency evaluation of the continuous flow electrocoagulation process for the treatment of oily-contaminated wastewater. *Ecological Engineering & Environmental Technology*, 25(12), 203–217. <https://doi.org/10.12912/27197050/194187>
- Hamawand, I. (2023). Energy consumption in water/wastewater treatment industry—Optimisation potentials. *Energies*, 16(5), 2433. <https://doi.org/10.3390/en16052433>
- Lefherz, H., Ahuis, M., Dilger, N., Kwade, A., Zellmer, S. (2025). Sustainability of electrode scrap recycling – Quantifying the environmental benefit of direct recycling routes for battery production scrap. *Journal of Energy Storage*, 132, 117688. <https://doi.org/10.1016/j.est.2025.117688>
- Liu, Z., Zhong, Y., Yu, Y., Xie, J., Wang, M., Guo, Z. (2024). Faradaic efficiency and anodic electrochemical behavior of Fe electrocoagulation: The role of co-existing ions and ultrasonic assistance. *Journal of Water Process Engineering*, 57, 104720. <https://doi.org/10.1016/j.jwpe.2023.104720>
- Mashale, K., Mogashane, T. M., Madzivha, P., Motlatle, M. A., Mokoena, L., Tshilongo, J. (2025). Iron oxide and hydroxides for the removal of heavy

- metals from wastewater. In *Current research on mineralogy: Minerals characterization and their applications*. IntechOpen. <https://doi.org/10.5772/intechopen.1010016>
20. Mazhandu, Z., Mashifana, T. (2024). Active pharmaceutical contaminants in drinking water: Myth or fact? *DARU Journal of Pharmaceutical Sciences*, 32(2), 925–945. <https://doi.org/10.1007/s40199-024-00536-9>
21. Naseri, S., Mousavi, S. A., Karami, S. (2022). Effects of electrode material and surface area on the performance of microbial fuel cells treating leachate. *Desalination and Water Treatment*, 253, 223–230. <https://doi.org/10.5004/dwt.2022.28305>
22. Obaid, Z. H., Salman, J. M., Kadhim, N. F. (2023). Review on toxicity and removal of pharmaceutical pollutants using immobilised microalgae. *Ecological Engineering & Environmental Technology*, 24(6), 44–60. <https://doi.org/10.12912/27197050/166013>
23. Popov, K., Živković, P., Nikolić, N. D. (2011). A mathematical model of the current density distribution in electrochemical cells. *Journal of the Serbian Chemical Society*, 76(6), 805–822. <https://doi.org/10.2298/JSC100312079P>
24. Sudiana, I. K., Sastrawidana, I. D., Sukarta, I. N. (2022). Adsorption kinetic and isotherm studies of Reactive Red B textile dye removal using activated coconut leaf stalk. *Ecological Engineering & Environmental Technology*, 23(5), 61–71. <https://doi.org/10.12912/27197050/151628>
25. Syaichurrozi, I., Sarto, S., Sediawan, W. B., Hidayat, M. (2020). Mechanistic models of electrocoagulation kinetics of pollutant removal in vinasse waste: Effect of voltage. *Journal of Water Process Engineering*, 36, 101312. <https://doi.org/10.1016/j.jwpe.2020.101312>
26. Szymański, W., Boczkal, S., Kapinos, D., Hrabia-Wisnios, J., Szymańska, E., Stobbe, L., Mager, T., Kościelski, M. (2026). Recycling of scrap metal from multifunctional aluminum-based electronic device housings. *Recycling*, 11(5), 88. <https://doi.org/10.3390/recycling11050088>
27. Tahreen, A., Jami, M. S., Ali, F. (2020). Role of electrocoagulation in wastewater treatment: A developmental review. *Journal of Water Process Engineering*, 37, 101440. <https://doi.org/10.1016/j.jwpe.2020.101440>
28. Touijer, A., Yahia, E. H., Saidi, M., Taouil, H., Allaoui, M., Ibn Ahmed, S. (2023). Removal of amoxicillin from an aqueous solution by activated carbon prepared from biomass. *Journal of Ecological Engineering*, 24(9), 63–79. <https://doi.org/10.12911/22998993/168350>
29. Vasudevan, S., Lakshmi, J., Sozhan, G. (2011). Effects of alternating and direct current in electrocoagulation process on the removal of cadmium from water. *Journal of Hazardous Materials*, 192(1), 26–34. <https://doi.org/10.1016/j.jhazmat.2011.04.081>
30. Wang, R.-S., Shan, L.-L., Zhu, Z.-B., Liu, Z.-Q., Liao, Z.-M., Cui, Y.-H. (2025). Current status of electrode corrosion passivation and its mitigation strategies in electrocoagulation. *Chemical Engineering and Processing – Process Intensification*, 209, 110192. <https://doi.org/10.1016/j.cep.2025.110192>
31. Weiss, S. F., Christensen, M. L., Jørgensen, M. K. (2021). Mechanisms behind pH changes during electrocoagulation. *AIChE Journal*, 67(11), e17384. <https://doi.org/10.1002/aic.17384>
32. Zhao, X., Wang, J.-Y., Wang, Y.-Q., Cui, C.-H., Yan, X., Dai, W., Zhang, A.-R., Zhang, Z.-Y., Tang, D.-D., Zhou, Y., Qin, Q., Pang, J.-W., Zhang, L.-Y., Ren, N.-Q., Ding, J., Yang, S.-S. (2025). In-situ formation of green rust during Fe(II) coagulation: Dual reductive and adsorptive pathways for dyeing wastewater treatment. *Water Research*, 285, 124174. <https://doi.org/10.1016/j.watres.2025.124174>