

RESEARCH ARTICLE

PARAMETRIC OPTIMIZATION OF ELECTROCHEMICAL HEAVY METAL REMOVAL FROM WASTEWATER: A CASE STUDY AT RUSTAMIYA TREATMENT PLANT

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ABSTRACT

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There is a serious impact of heavy metals in waste water which threatens environmental and human health and this therefore encourages a need to find appropriate ways to treat this waste water productively. The paper entails the electrochemical treatment of lead (Pb) and cadmium (Cd) contaminants out of industrial wastes, which were sampled in the Rustamiya sewage facility in Baghdad, Iraq. The three types of anode materials namely, copper, iron and stainless steel have been tested under different operating variables such as voltage (20-30 V), initial metal concentration (10-25 ppm), the distance between the pair of electrodes (1-4 cm) as well as different pH conditions (4-10). Copper anodes also exhibited the most efficient removal at 88 percent removal of lead and 80 percent removal of cadmium but with the main cause being of Cu (OH)₂ that increases the precipitation of the contaminants. The stainless steel was however suggested to be more sustainable, as it is longer lasting, less toxic and resistant to corrosion. It was also shown that a greater pH value and harder voltages enhanced removal efficiency whereas a greater initial concentration and greater electrode spacing impaired it. Such results raise the possibility of maximized electrochemical techniques towards sustainability in wastewater treatment system in the remediation of heavy metals.

KEYWORDS

Electrochemical Treatment, Heavy Metal Removal, Lead and Cadmium, Wastewater Treatment, Electrode Materials, Parametric Optimization.

1. INTRODUCTION

The management of wastewater can broadly be overwhelmed with four key points, which are minimization of pollution, collection and purifying wastewater as alternative resource of water, as well as generation of valuable by-products (Gooijer et al., 2017). Latest accounts reveal that a number of industries have also come up with different waste water treatment processes. Conversely, the fundamental gist of the present research study is wastewater treatment with the presence of heavy metal. Reclamation of wastewater has Physio-chemical techniques, which are many. However, the majority of these regimes were less practically reliable or have low benefits and high cost. As such, a number of approaches have been introduced, which include activated carbon adsorption, chemical coagulation, ultraviolet (UV) driven photodegradations, hydrodynamic cavitation, sonochemical degradations, ozonation, membrane filtration, and electrochemical processes, etc (Asli and Taghizadeh, 2020).

Electrochemical techniques, such as electrocoagulation, electrochemical Fenton process, and electro-oxidation, have recently attained significant interest in industrial wastewater treatment (Amin and Elsayed, 2024). Electrochemical techniques have dramatic abilities for wastewater due to their varied ecological compatibility, higher operation efficiency, and cost-efficiency. Each heavy metal is related to a certain health issue. According to recent information on the WHO website, arsenic (As), cadmium (Cd), lead (Pb), and mercury (Hg) are among the ten chemicals that constitute a detrimental risk to human health as of June 1, 2020 (Perrelli et al., 2022). The various technological, medicinal, and agricultural applications of

these metals have a dangerous impact on health (WHO, 2021).

This study aims to apply the electrochemical method to remove heavy metals, specifically (lead and cadmium) from wastewater. This process is done by dissolving lead and cadmium salts in a certain proportion in distilled water in the laboratory.

- To study the effect of important operational parameters on the removal efficiency of TDS, EC and metal removal efficiency
- To study different parameters (applied voltage, electrolyzation time, electrode distance), then use the optimum results.
- To determine the efficiency of the system at different concentrations of heavy metals.
- To determine the most efficient electrode types (Cu-, Cu+), (Cu-, Fe+), (Cu-, St. St+) that achieve the highest percentage of heavy metal removal.

2. CASE STUDY SITE AND CHARACTERIZATION

The experimental tests included conducting experiments on samples from the Rustamiya wastewater treatment plant (Figure 1 shows the plant location) and other experiments on laboratory-prepared samples of heavy metals. Electrochemical methods were applied to these samples, aiming to achieve the best removal percentage of heavy metals by treating different parameters. The electrochemical technical experiments included the use of three types of anodes (copper, stainless steel, and iron), while copper was used as the cathode for each type of anode.

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Figure 1: Location of Rustamiya Plant.

3. EXPERIMENTAL METHODS

The current study included the two major steps, which ensured electrochemical treatment of real wastewater of Rustamiya origin and synthesis of the lab-generated samples. The purpose of the experiments in both parts was to find out the removal of Pb, Cd and total dissolved

solids (TDS) upon the changed factors, such as the voltage, pH, initial concentration, electrode material, and electrode spacing.

3.1 Test Variables

The test variables as shown in table 1. Are regarding to voltage, electrode, initial concentration, ph and electrode spacing parameters

Table 1: Experimental Test Procedures		
Parameter	Wastewater Samples	Synthetic Samples
Voltage (V)	20, 25, 30	20, 25, 30
Electrodes	Cu-Cu, Cu-Fe, Cu-St. St	Cu-Cu, Cu-Fe, Cu-St. St
Initial Concentration (ppm)	Pb = 2.81, Cd = 1.2	10, 15, 20, 25
pH	8.1	4, 5, 7, 9, 10
Electrode Spacing (cm)	4	1, 2, 4

3.2 Equipment and Chemicals

Such laboratory equipment was used. The source and regulator of the power supply was a direct-current (DC). Such analytical equipment was used as a TDS meter, a pH meter, a turbidity meter, and an atomic absorption spectrometer, complemented by usual laboratory equipment. Valuable chemicals used in the experiment were Pb(NO3)2, Cd(NO3)2·4H2O, NaCl used to Increases ion concentration to improve solution electrical conductivity, HCl and NaOH to serve as pH regulators and Distilled water, these tools are used exactly for the removal of heavy metals in water (Boinpally et al., 2023; Chowdhury et al., 2019; Bakry et al., 2018; Merzouk et al., 2009)

3.3 Electrode Specifications

Cylindrical pieces of Cu, Fe and St. St of dimensions, r = 0.75 cm and h = 15 cm respectively, were taken as the working electrodes because copper had high electrical conductivity, iron promoted reactive coagulation and stainless steel ensured corrosion resistance throughout the operation (Shaker et al., 2020; Butler et al., 2011; Gök and Gülyavaş, 2025).

3.4 Test Execution and Observations

Wastewater tests: The test temperature of 25+/-2 o C and the electrode spacing were fixed at 4 cm. The voltage changes were made and the rotation of colors and generation of deposits and gases observed visually, the samples are shown in figures (2,3 and 4)

a) Cu-Cu: Blue color (Cu²⁺), visible deposits.



Figure 2: Wastewater samples using electrodes (Cu-, Cu+) and voltage 30.

b) Cu-Fe: Orange precipitates, gas bubbles.



Figure 3: Wastewater samples using electrodes (Cu-, Fe+) and voltage 30.

Cu-St. St: Lighter discoloration, precipitate layer.



Figure 4: Wastewater samples using electrodes (Cu-, St. St+) and voltage 30.

- Synthetic sample tests: Conducted to evaluate individual parameters:
- Effect of concentration: 10–25 ppm, best removal at 10 ppm.



a. (Cu-, Cu+)



b. (Cu-, Fe+)

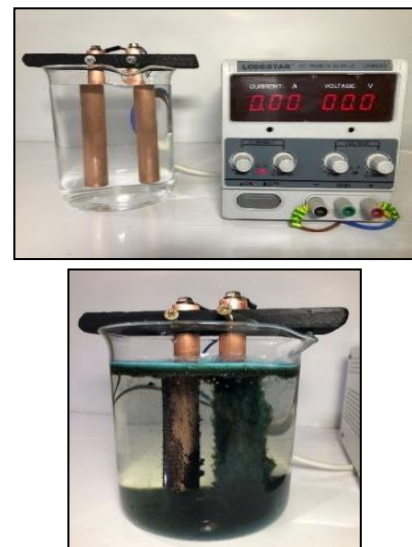


B. (Cu-, St. St+)

Figure 5: Determine the optimum concentration at PH=7, d=2cm, voltage 25.

As showing in Figures (6,7 and 8) the samples tested and the outcomes are:

- Effect of pH: Best removal at pH 9.
- Effect of voltage: Best removal at 30 V.
- Electrode spacing: Best performance at 1 cm due to reduced resistance



(Cu-, Fe+)



(Cu-, Cu+)



(Cu-, St. St+)

Figure 6: Determine the optimum pH at concentration=10 ppm, d=2cm, voltage 25.



(Cu-, Cu+)



(Cu-, Fe+)

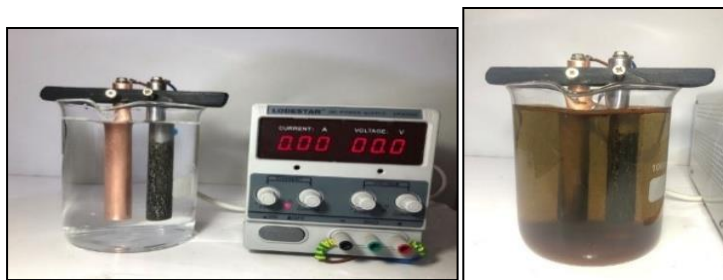


(Cu-, St. St+)

Figure 7: Determine the optimum voltage at pH =9 at concentration =10 ppm, d=2cm



(Cu-, Cu+)



(Cu-, Fe+)



(Cu-, St. St+)

Figure 8: Determine the optimum distance between electrodes at PH =9 at concentration =10 ppm, voltage 30.

4. RESULTS OF WASTEWATER TREATMENT

4.1 Overview of Electrochemical Wastewater Treatment Results

The influence between the applied voltage and treatment time on the removal efficiency was well evaluated systematically at 20, 25 and 30 V electrochemical potentials keeping the electrode-electrolyte distance constant at 4 cm. To ascertain the particular coagulants formed during the electrolysis of Cu with Cu, Cu and Fe, and Cu and St. St, three different

set ups involving three electrodes, that were Cu-Cu, Cu-Fe, and Cu-St. St were observed. A monitoring using in-situ electro-chemical measurements was imposed on total dissolved solids (TDS), lead (Pb), and cadmium (Cd) during treatment.

4.2 Influence of Electrode Type, Voltage, And Time

In all the electrode pairs that had been tested, the increase in electrode potential and the electrolysis time progressively enhanced a removal rate of each contaminant, as shown in Figure 9.

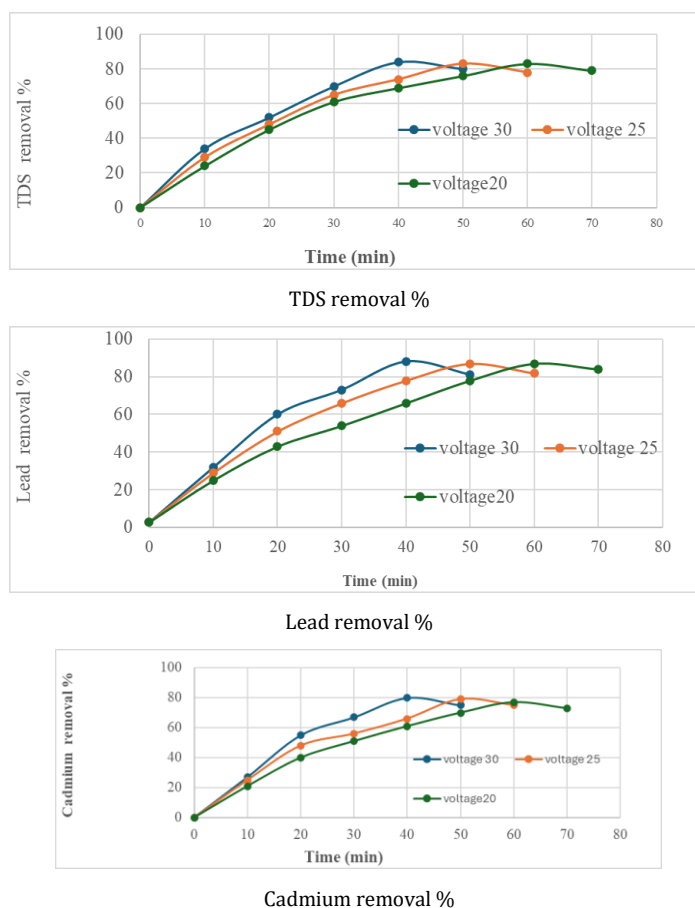


Figure 9: Effect of Time and Applied Voltage Using Electrodes material (Cu-, Cu+).

As shown in Figures (10, 11 and 12) the TDS removal %, Lead removal %, and Cadmium removal % regarding the targeted parameters shows:

- The combination Cu-Cu provided the strongest effects among the three electrode systems: reduction of TDS amounted to 84%, depletion of Pb- to 88% and Cd- over 80%. Such extremely desirable results may be credited to fast combination between Cu (OH)₂ precipitate which is aided by high levels of Cu²⁺. This matches the results in the literature (Castro et al., 2023; Bakry et al., 2024)
- Cu-Fe and Cu-St. St systems provided slightly worse performances, and Pb and Cd removal rates were at ~84 and ~78 %, respectively, which could be explained by the differences in the kinetics of metals dissolution and coagulant stability, which matches the literature as well (Gök and Gülyasar, 2025).

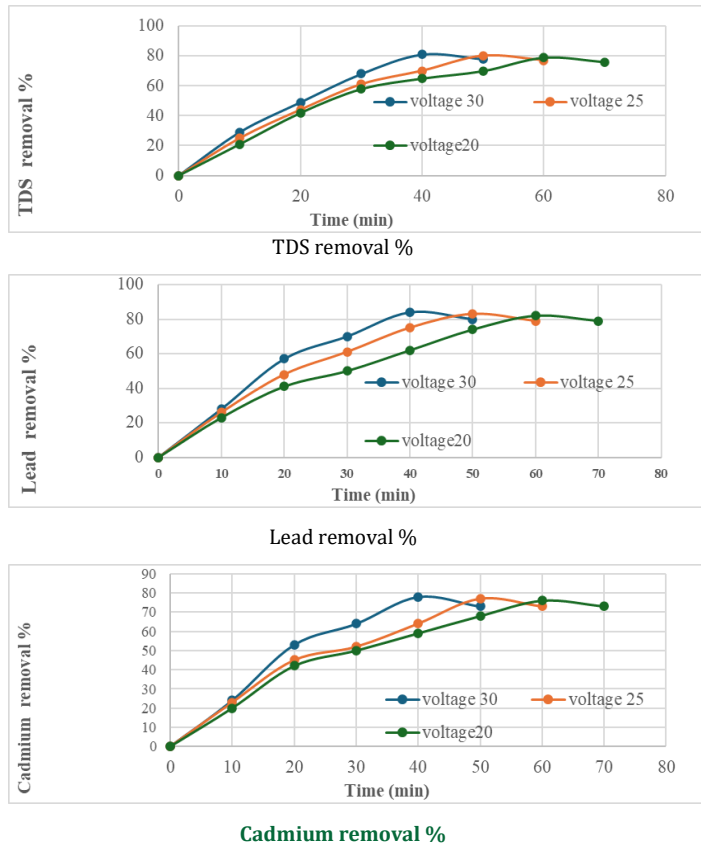


Figure 10: Effect of Time Electrolyzation and Applied Voltage Using Electrodes material (Cu-, Fe+).

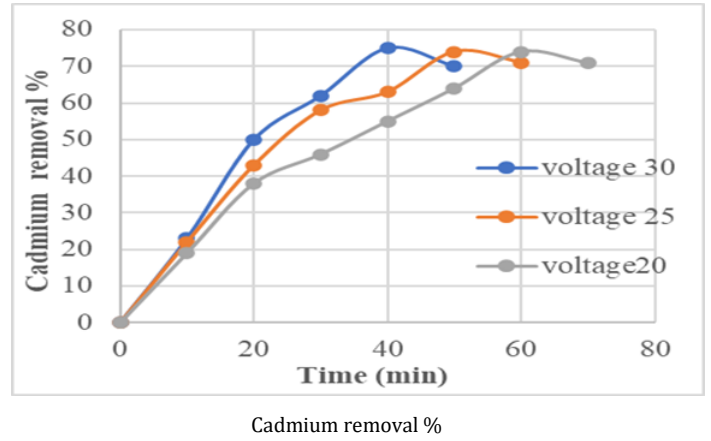
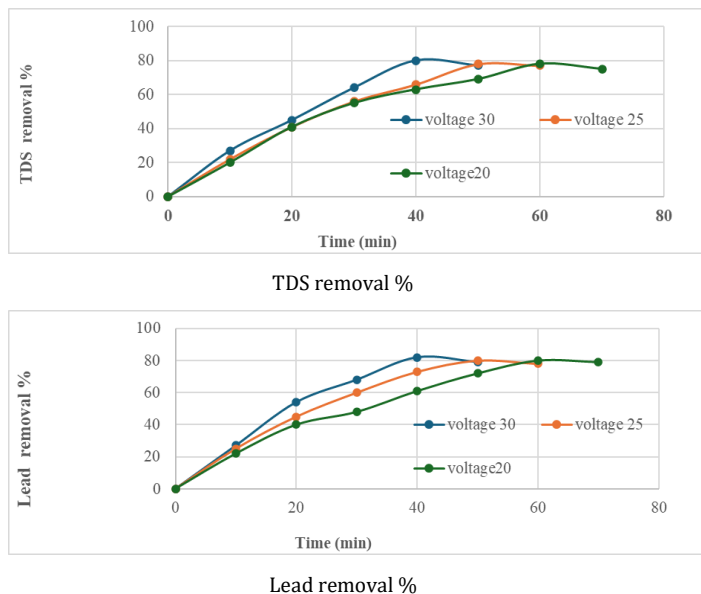


Figure 11: Effect of Time Electrolyzation and Applied Voltage Using Electrodes material (Cu-, St. St+).

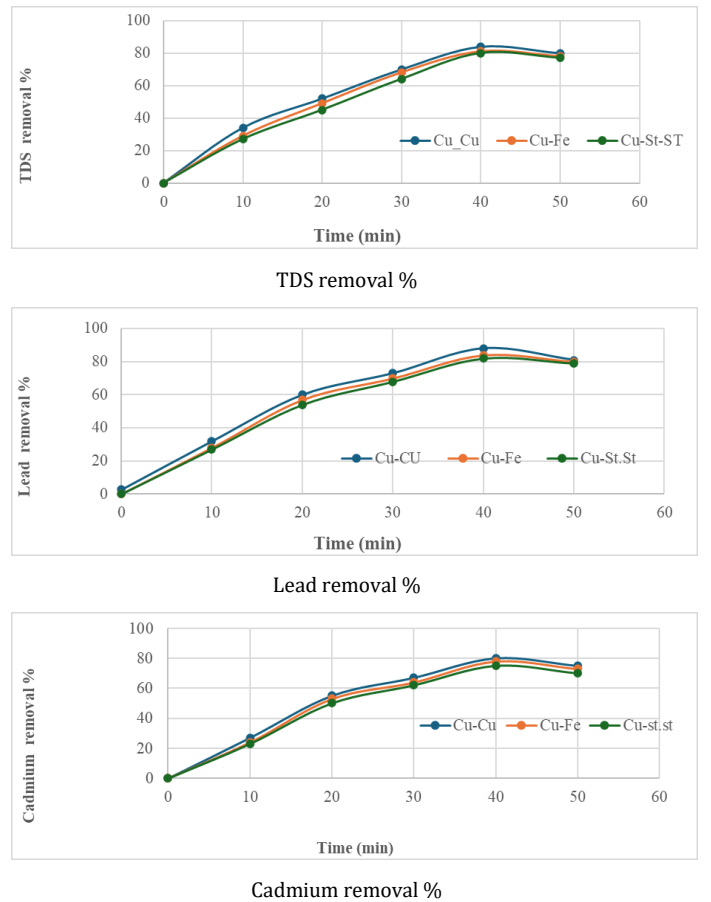


Figure 12: Impact of electrodes material on removal efficiency.

Efficiency was observed to decline after ~40 min as a result of the onset of anode passivation and the resultant increase in pH above 10, which probably due to the catalyzing effect of supersaturation on re-dissolution of the metal hydroxides. These observations match the literature (Ingelsson et al., 2020; Phu et al., 2025).

4.3 Effect of Electrode Material

The effectiveness of every arrangement was also considered a matter of the original concentration of a contaminant. In the case of Pb and Cd, the highest removal efficiencies were calculated at 10 ppm that is the point at which electrode saturation is evident. These statistics prove the drawbacks of concentrated feeds, as well as the significance of the dilution before the treatment. Regarding the type of electrode to use, it was discovered that stainless steel presents the most desirable and environmentally friendly solution to use since it is not toxic and lasts longer, which match the findings by (Abdel-Shafy et al., 2022).

4.4 Parameter Optimization with Synthetic Samples

Initial Concentration: The highest efficiency was obtained at 10 ppm of

both Cd and Pb regardless of the electrode material; the removal efficiency values of copper, iron, and stainless steel were around 99.9, 94 and 90 %, respectively which mirrors the trends in recent studies (Un and Ocal, 2015). The higher the concentration, the less was its efficiency as the surfaces of the electrodes were saturated above 10 ppm and it matches the results shown in recent research (Licht et al., 2022), as shown in Figures (13 and 14)

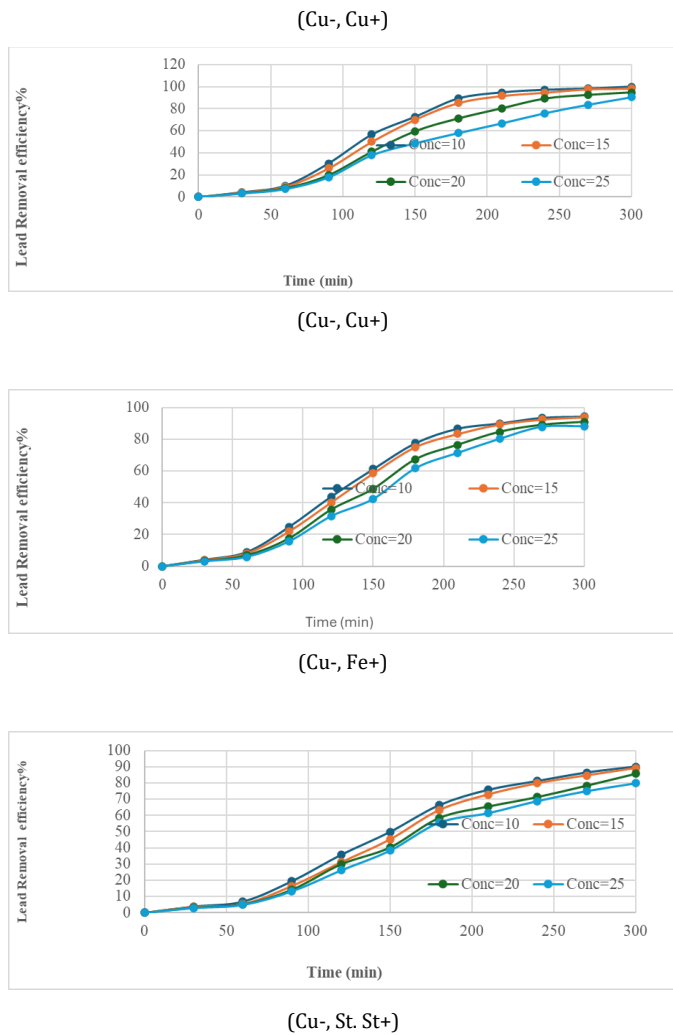


Figure 13: Impact of initial concentration on Lead Elimination Percentage.

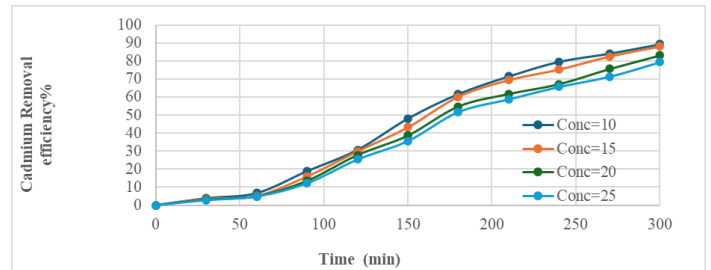
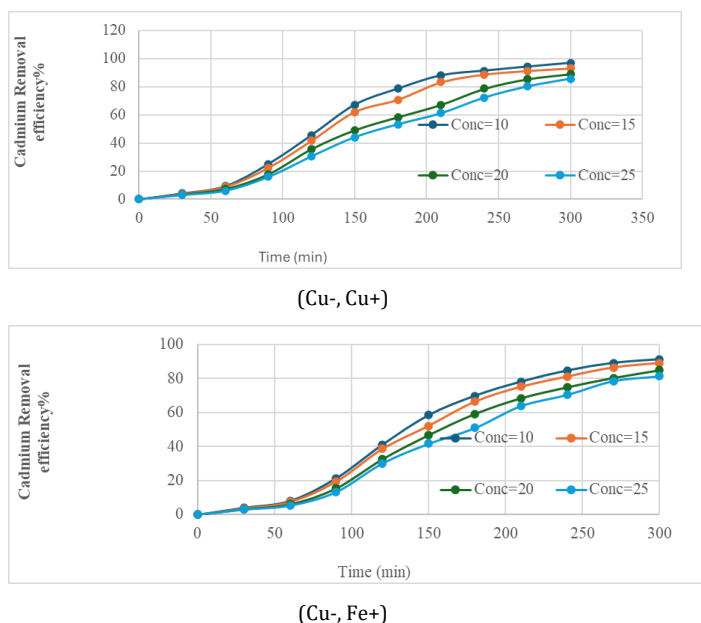


Figure 14: Impact of initial concentration on Cadmium Elimination Percentage.

pH: Solution pH variations also delivered more information about removal. The maximum removal was at pH 9, which was also the condition that represented maximum solubility of hydroxide; the lower pH (< 7) prevented precipitation, because the amount of OH is insufficient to form large quantities of insoluble precipitates, and pH > 10 favored the redissolution of precipitated solids since the metals form soluble $[Pb(OH)_4^{+}]$, $[Cd(OH)_3^{+}]$ complexes, as shown in Figure (15) (Bhagawan et al., 2014; Parga Torres, 2024; Jonasi et al., 2017).

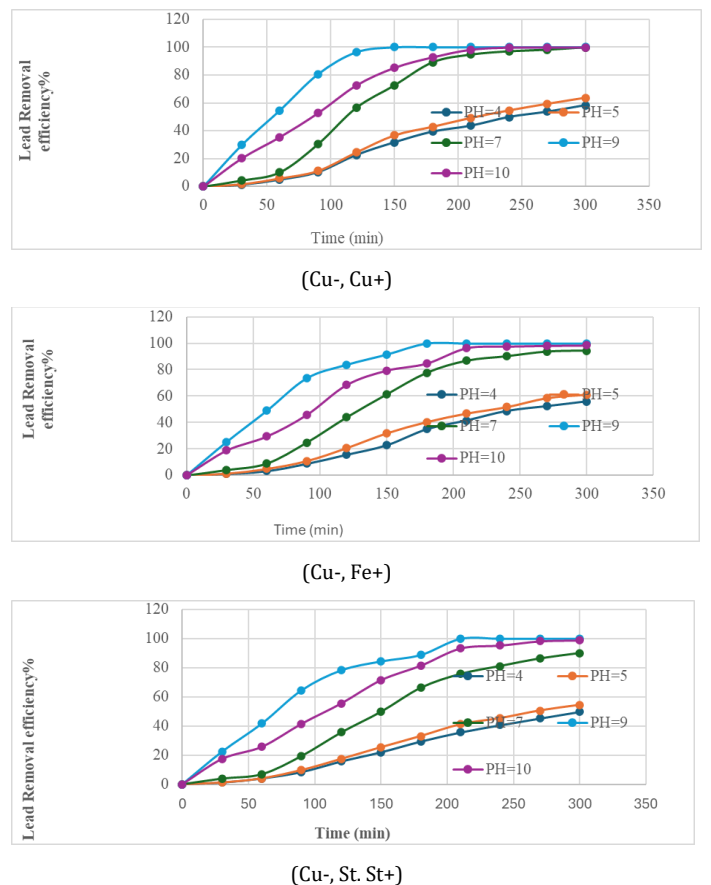
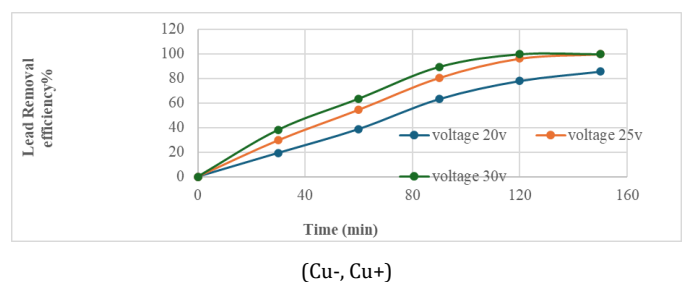


Figure 15: Impact of pH on Lead Elimination Percentage.

Voltage: Increasing the voltage accelerated electrochemical movement of the ion and also amplified the effectiveness of the flotation removal procedures. All the configurations produced almost complete removal of Pb and Cd at 30 V, these findings match the literature, as shown in Figure (16 and 17) (Khan et al., 2023; Merzouk et al., 2009).



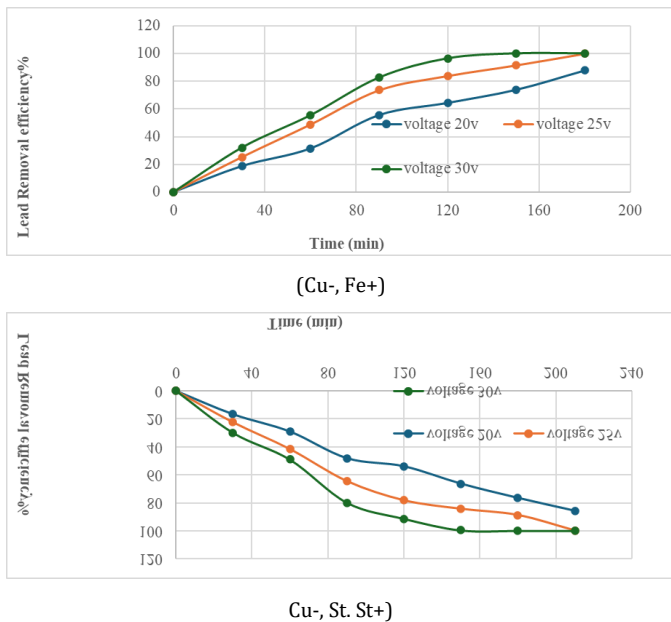


Figure 16: Impact of Voltage on Lead Elimination Percentage.

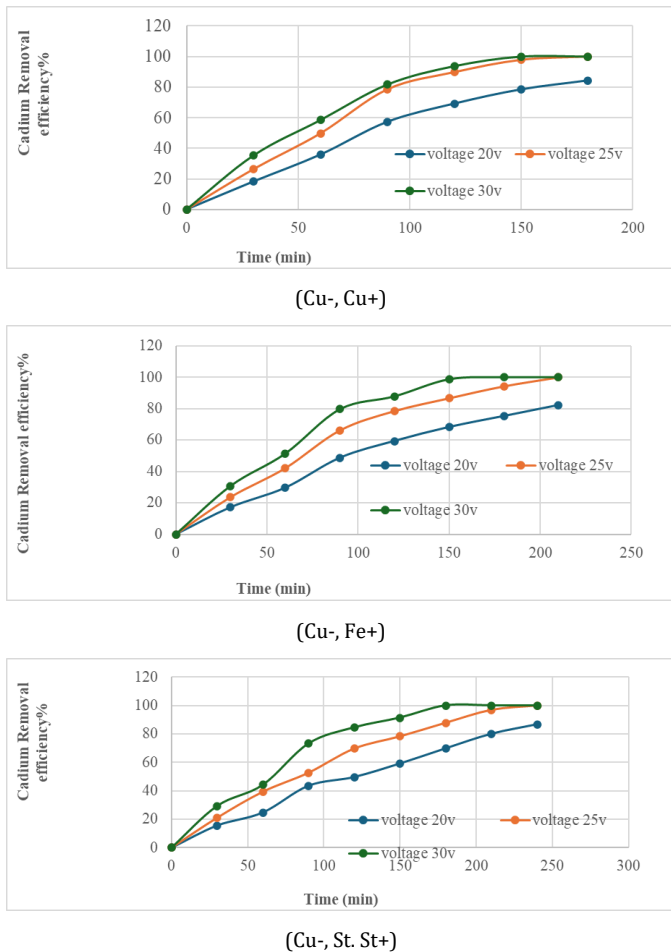


Figure 17: Impact of Voltage on Cadmium Elimination Percentage
Electrode Distance: A 1 cm spacing gave the highest removal (>99.9%) due to lower resistance and higher current density. Distances ≥ 4 cm reduced efficiency, these findings match the literature in the cases of Cd and Pb, as shown in Figures (18 and 19) (Brahmi et al., 2015; Ammar et al., 2024).

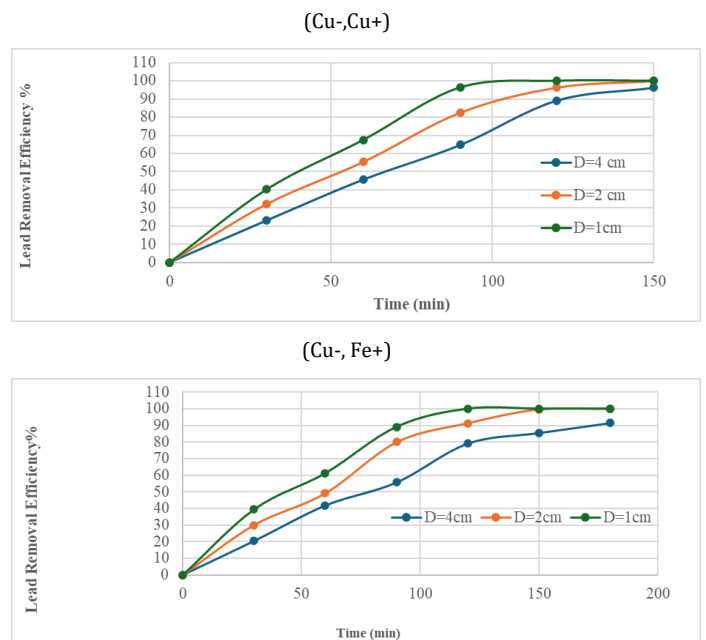
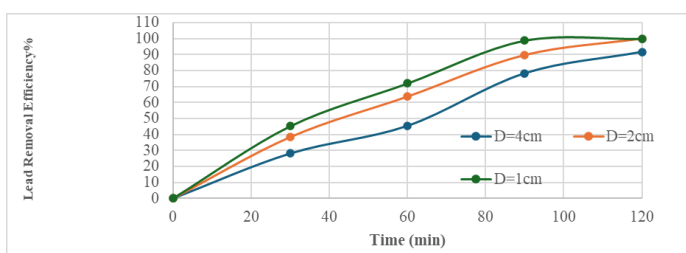


Figure 18: Effect of distance between electrodes on Lead Removal Efficiency.

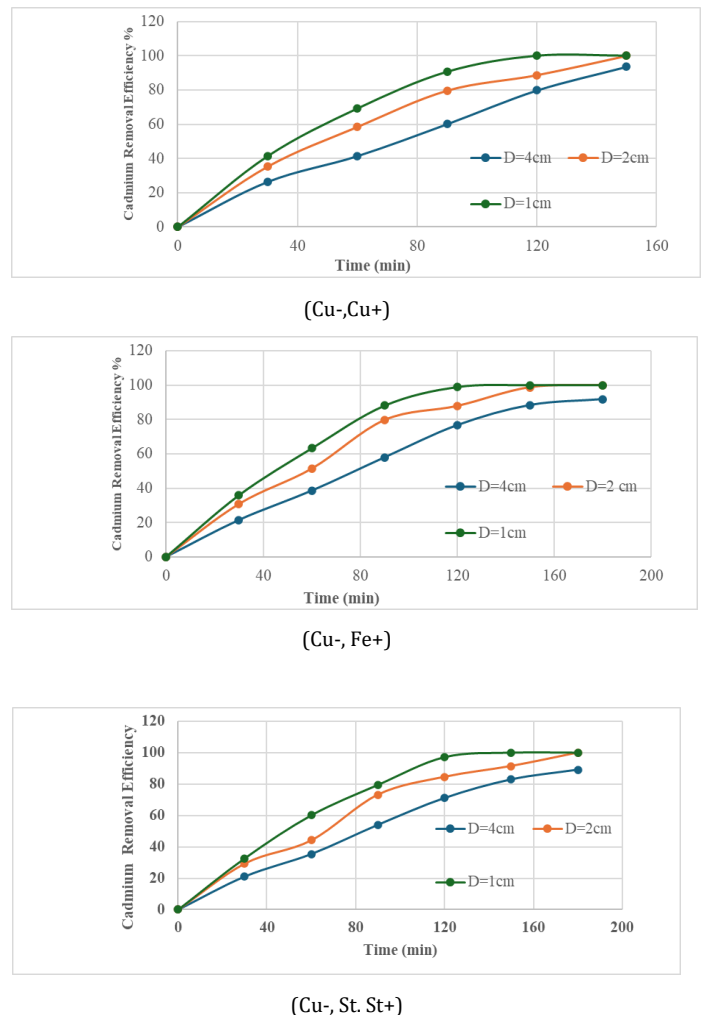


Figure 19: Effect of distance between electrodes on Cadmium Removal Efficiency

Research work has shown the tremendous effectiveness of copper anode in the elimination of Cd and Pb but at the same time, it raises grave toxicity issues, These finding match the literature (Chowdhury et al., 2019). Nevertheless, using Copper is more feasible but it increases toxicity according to previous research (Peng et al., 2011). The stainless-steel sheet electrode comes out as an alternative, this finding is

supported by recent research which shows that Stainless steel have the same removal performance as the Copper (Dura and Breslin, 2019). This maximum removal efficiency was achieved under the following conditions and parameters; namely: 10 ppm of lead, medium pH of 9 and showed the applied potential of 30 V as against a spacing of 1 cm, this closely match the study indicated by (Brahmi et al., 2014).

5. CONCLUSION AND RECOMMENDATIONS

In order to evaluate the applicability of electrochemical treatment in remediation of heavy metals (Pb, Cd) and total dissolved solids (TDS) in waste-water, simple experiments were taken out with three different anode materials- that is, copper, iron and stainless steel as well as a copper cathode. The actual sample of the Rustamiya wastewater and the artificial sample prepared in the laboratory were done at different conditions of work (voltage, time of electrolysis, pH, initial sample concentration and the distance between electrodes).

Its main conclusions are the following.

- The electrodes that showed the greatest levels of removal efficiency (Pb 88%, Cd 80%, and TDS 84%) were the copper-copper electrodes owing to the synthesis of effective Cu (OH) 2 coagulants and greater electroflotation.
- Copper-iron and copper-stainless steel systems were a bit less effective, which is caused by a lower amount of released ions and a decrease in coagulant production; stainless steel was the least effective.
- The factors of voltage and the electrolysis time were positively correlated with removal efficiency; with 30 V, 40 minutes, the efficiency was the highest.
- The best pH was 9 whereby hydroxide ions helped in precipitating Pb and Cd as hydroxide compounds. At very high alkaline concentrations efficiency deteriorated as a result of re-dissolution of such precipitates.
- Starting levels of lower concentration (10 ppm) resulted to higher removal efficiency since electrode surface was optimised.

The smallest electrode spread (1 cm) resulted to best performance due to the lower resistance and high current density. Although the copper anode has a high performance, stainless steel is preferentially applied in the practice due to toxicity of copper and possible risk to the environment.

5.1 Recommendations

Resting on the results of investigations, the proposed recommendations are as follows:

- Full-scale applications ought to adopt stainless steel anodes to ensure safety, high durabilities, and low environmental risks.
- An optimum level should be maintained at the established operational parameters so as to ensure optimal removal of the electrode parameters such as pH 9, applied voltage of 30 V and distance separation of electrodes as 1 cm.
- Research should be done on the surface treatment of the electrodes i.e. decoring of the electrodes or alloying of the electrodes to improve the effectiveness of the stainless steel.
- Cleaning or regular polarity reverse should be adopted to reduce electrode passivation and maintain a long-life performance.
- The experiment ought to be carried to other heavy metals and pollutants to confirm the flexibility of the electrochemical technique.
- Research on integration of the electrochemical treatment with the renewable energy (especially in decentralized wastewater treatment systems) is justified.

Overall, the research proves that electrochemical treatment is a feasible and scalable process of eliminating heavy metals in wastewater that may be implemented in practice with further optimization.

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