

Development of An Electrolytic Bin for Treatment of Ionic Pollutants in Sewage From Chemical Laboratories

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Abstract: Chemical laboratories generate wastewater containing potentially hazardous metal ions that can threaten environmental quality and public health if discharged without adequate treatment. This study aimed to develop and evaluate a laboratory-scale electrolytic bin for removing copper, lead, chromium, and zinc from simulated chemical laboratory wastewater. The system employed an electrochemical cell with aluminium and stainless-steel electrodes, and treatment performance was assessed over three hours using atomic absorption spectroscopy (AAS). The initial concentrations of copper, lead, chromium, and zinc were 0.902, 0.724, 0.830, and 0.589 mg/L, respectively. After one hour, their concentrations decreased to 0.301, 0.531, 0.623, and 0.408 mg/L, corresponding to removal efficiencies of 66.63%, 26.66%, 24.94%, and 30.73%, respectively. After two hours, copper concentration reached 0.002 mg/L, representing 99.78% removal, while lead, chromium, and zinc concentrations decreased to 0.120, 0.221, and 0.343 mg/L, respectively. Following three hours of treatment, lead, chromium, and zinc concentrations declined further to 0.003, 0.006, and 0.004 mg/L, corresponding to removal efficiencies of 99.59%, 99.28%, and 99.32%, respectively. The three-hour copper concentration was reported below the detection limit. The wastewater pH increased from 5.5 to 7.0 during treatment. The observed reductions may involve electrocoagulation, adsorption, precipitation, and potentially electrodeposition, although their individual contributions require further investigation. The findings demonstrate the potential of the electrolytic bin for reducing metal concentrations in simulated laboratory

wastewater. Further validation using replicate experiments, actual laboratory effluents, and verified AAS measurements is necessary before practical deployment.

Keywords: Electrolytic bin; Heavy metals; Wastewater treatment; Electrocoagulation; AAS

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1.0 Introduction

Chemical laboratories in universities, research institutions, industries, and analytical facilities generate wastewater containing a wide range of potentially hazardous chemical substances. Depending on the experiments conducted, these effluents may contain dissolved metal ions, acids, alkalis, inorganic salts, organic solvents, and reaction by-products. Among these contaminants, heavy metals such as copper, lead, chromium, and zinc are of particular environmental concern because their persistence, toxicity, and potential accumulation in biological systems can threaten aquatic organisms and human health. Unlike many organic pollutants, metals cannot be destroyed through conventional chemical or biological degradation; rather, they must be removed from the wastewater, transformed into less hazardous forms, or recovered for appropriate reuse or disposal (Fu & Wang, 2011; Fei & Hu, 2023). Consequently, the effective treatment of chemically contaminated laboratory wastewater is an important component of environmental protection and responsible laboratory waste management.

The management of laboratory wastewater presents particular challenges because its composition and contaminant concentrations may vary considerably with the nature of the experiments, reagents, and analytical procedures performed. Some laboratory effluents contain mixtures of dissolved metal ions and other chemicals that may interfere with conventional treatment processes. Where such wastewater is inadequately treated before discharge, it may contaminate drainage systems, surface water, and soil, creating potential ecological and public health risks. In developing countries, including Nigeria, the need for practical and affordable wastewater treatment technologies is particularly important for institutions with limited treatment infrastructure and financial resources. Previous studies have examined wastewater treatment

challenges and conventional remediation methods, including chemical precipitation, coagulation, and filtration (Hutnan *et al.*, 2024; Kim *et al.*, 2018). Although these methods can effectively remove certain contaminants, their performance depends on wastewater composition and operating conditions, and their application may require chemical reagents, multiple treatment stages, and additional sludge-management procedures (Manikandan *et al.*, 2022).

Conventional chemical treatment generally involves the addition of reagents to adjust pH, precipitate dissolved metals, or destabilize suspended and colloidal particles. Aluminium sulphate, ferric chloride, and ferrous salts are commonly used as coagulants in appropriate treatment applications. The resulting precipitates and aggregates are subsequently separated through sedimentation, filtration, or related physical processes. However, chemical consumption, sludge production, operational complexity, and the need for effective residual-waste management can limit the suitability of conventional treatment systems for decentralized applications. These limitations have encouraged the investigation of electrochemical technologies as alternative or complementary approaches to wastewater treatment (Mollah *et al.*, 2001; Sahu *et al.*, 2014).

Electrochemical wastewater treatment employs electrical energy to initiate reactions at electrode surfaces or generate reactive species within the treatment medium. Major electrochemical processes include electrocoagulation, electro-oxidation, electroreduction, electrodeposition, and electroflotation (Chen, 2004; Feng *et al.*, 2016). Their potential advantages include compact equipment configurations, controllable operating conditions, reduced dependence on externally added treatment chemicals in some applications, and



opportunities for pollutant removal or resource recovery.

Electrocoagulation involves the dissolution of sacrificial metal electrodes, usually aluminium or iron, under an applied electric current. The released metal ions undergo hydrolysis and generate metal hydroxide species that destabilize suspended particles and facilitate the removal of dissolved contaminants through adsorption, complexation, coprecipitation, and floc formation. Hydrogen bubbles generated at the cathode may also promote the flotation of contaminant-bearing flocs. The effectiveness of electrocoagulation depends on factors such as electrode composition, current density, initial pH, electrolysis duration, electrode spacing, and solution conductivity (Mollah *et al.*, 2001, 2004; Sahu *et al.*, 2014). Previous research has demonstrated the applicability of iron- and aluminium-based electrocoagulation systems to wastewater treatment, although performance varies with the wastewater matrix and operating conditions (Kobyas *et al.*, 2003). Electrodeposition, in contrast, involves the electrochemical reduction of suitable dissolved metal species and their deposition on a cathode. This process can facilitate the recovery of metals from wastewater while reducing their concentrations in the treated solution. Its effectiveness depends on the electrochemical properties of the target metal, electrode material, applied potential, pH, competing ions, and the presence of complexing agents. Electro-oxidation involves oxidation reactions at the anode, either directly at the electrode surface or indirectly through electrochemically generated oxidizing species. It is particularly relevant to the transformation of oxidizable contaminants and is not equivalent to electrodeposition or electrocoagulation (Chen, 2004; Feng *et al.*, 2016). For metal-containing wastewater, the selection of an appropriate electrochemical mechanism is essential because changes in metal oxidation state do not

necessarily result in the removal of the metal from the aqueous phase.

Recent reviews have continued to examine electrochemical reactor configurations and their suitability for heavy-metal removal and recovery. Kew *et al.* (2025) discussed the importance of reactor design, electrode materials, and target-specific operating conditions in determining treatment performance. Similarly, reviews of electrochemical oxidation and reduction have highlighted the potential of these processes for metal removal and recovery while identifying challenges associated with complex wastewater composition, process optimization, and practical scale-up (Progress and challenges in the use of electrochemical oxidation and reduction processes for heavy metals removal and recovery from wastewaters, 2024). These findings indicate that electrochemical treatment remains a promising research area, but the effectiveness of a particular system must be established experimentally rather than assumed from the general advantages of the technology.

The performance of electrochemical systems is strongly influenced by current density, initial pH, and treatment duration. Current density affects the rate of electrode dissolution and the extent of electrochemical reactions, although excessive current may increase energy consumption and promote competing reactions. Solution pH influences metal speciation, electrode reactions, hydroxide formation, and the solubility of metal-containing precipitates. Electrolysis duration determines the period available for contaminant removal, but prolonged operation may increase energy consumption without producing a proportionate improvement in treatment efficiency. Solution conductivity and electrode configuration also influence cell resistance and overall process performance (Mollah *et al.*, 2004; Sahu *et al.*, 2014). Therefore, systematic evaluation of these



variables is necessary when developing a treatment unit intended for practical application.

Several studies have investigated electrochemical treatment as a potentially cost-effective and environmentally compatible approach to wastewater remediation. Liu *et al.* (2022) discussed electrochemical treatment technologies in relation to the removal of contaminants from wastewater, while Ogundele *et al.* (2023) reported on the potential of electrochemical approaches for treating different classes of pollutants. Nelson *et al.* (2025) also examined electrocoagulation in the context of sustainable wastewater treatment and emerging contaminants. Although such studies provide a basis for understanding the wider applications of electrochemical technologies, their findings must be interpreted according to the contaminants, reactor configurations, and treatment conditions investigated. Research on industrial wastewater or emerging organic contaminants cannot, by itself, establish the effectiveness of a particular system for treating mixed metal-ion solutions generated by chemical laboratories. Despite advances in electrochemical wastewater treatment, the practical management of chemically contaminated laboratory effluents requires treatment units that are compact, affordable, easy to operate, and adaptable to the relatively small and variable wastewater volumes generated by individual laboratories. The literature reviewed provides evidence of the potential of electrocoagulation, electrodeposition, and other electrochemical processes; however, the suitability of a locally fabricated, mobile electrolytic bin incorporating appropriate electrode materials for the simultaneous treatment of selected metal ions under controlled operating conditions requires specific experimental evaluation. In particular, the effects of current density, initial pH, and electrolysis duration must be established for the

proposed system. The treatment performance must also be assessed through measurements of residual metal concentrations rather than removal percentages alone. This need provides the basis for developing and evaluating an electrolytic bin specifically intended for laboratory wastewater management.

The aim of this study was to design, construct, and evaluate the performance of a laboratory-scale batch electrolytic bin for treating wastewater containing selected ionic pollutants. Specifically, the study investigated the effects of current density, initial pH, and electrolysis duration on the removal of copper, lead, chromium, and zinc ions from synthetic laboratory wastewater using an aluminium/iron anode and a stainless-steel cathode configuration. The study also sought to identify operating conditions associated with high removal efficiencies and to assess the potential applicability of the developed unit to decentralized laboratory wastewater treatment. The significance of this study lies in its potential contribution to improved chemical laboratory waste management, environmental protection, and the development of locally fabricated wastewater treatment equipment. By evaluating a compact electrolytic bin under controlled conditions, the study provides experimental information on the influence of operating parameters on metal-ion removal and establishes a basis for further development of decentralized treatment systems. The findings may be useful to universities, research laboratories, and other facilities seeking practical approaches to managing metal-containing wastewater. Nevertheless, routine implementation would require further validation using actual laboratory effluents, assessment of energy and operating costs, appropriate management of metal-bearing sludge and electrode deposits, and confirmation that treated wastewater meets applicable discharge requirements.



2.0 Materials and Methods

2.1 Study Area and Experimental Location

The electrolytic bin was fabricated by an engineer at the institution identified in the original study records as Cross River University of Technology (CRUTECH), subsequently renamed the University of Cross River State (UNICROSS). The experimental investigation was conducted in the Chemistry Laboratory of the University of Calabar, Calabar, Cross River State, Nigeria. The laboratory provided the facilities required for the operation of the electrolytic bin, treatment of wastewater samples, measurement of physicochemical parameters, and determination of metal concentrations. All experimental procedures were conducted using appropriate laboratory practices and safety precautions.

2.2 Research Design

The study adopted an experimental research design involving the development, construction, and performance evaluation of a laboratory-scale electrolytic bin for the treatment of wastewater containing selected ionic pollutants. The investigation focused on the removal of copper, lead, chromium, and zinc ions under controlled electrochemical treatment conditions. The performance of the system was evaluated by determining metal concentrations and selected water quality parameters before and after treatment.

The experimental variables included current density, initial pH, and electrolysis duration. These parameters were investigated to determine their influence on treatment efficiency and to identify operating conditions associated with effective pollutant removal. The wastewater source used in each experimental phase must be specified consistently in the final manuscript. Where synthetic wastewater was used, the initial concentrations of the target metal ions were controlled during preparation. Where actual laboratory wastewater was treated, its initial

composition was determined experimentally before treatment.

2.3 Materials, Reagents, and Equipment

The materials and equipment used for the construction and operation of the electrolytic bin included a high-density polyethylene (HDPE) reactor vessel, aluminum anode, stainless-steel cathode, 12 V direct-current (DC) power source, insulated electrical wires, connectors, switching mechanism, current indicator, and voltage or current regulation components. The equipment used for experimental measurements included an atomic absorption spectrophotometer (AAS), digital pH meter, conductivity meter, thermometer, turbidity meter, beakers, measuring cylinders, and stirring rod.

Additional reagents and consumables required for sample preparation and analysis included analytical-grade chemicals for pH adjustment, calibration standards for metal determination, and appropriate containers for sample collection and storage. Where synthetic wastewater was prepared, suitable metal salts of copper, lead, chromium, and zinc were required to obtain the desired initial concentrations.

The actual capacity of the reactor vessel must also be confirmed from the fabrication records because the original description gives both 12 L and 25 L

2.4 Design and Construction of the Electrolytic Bin

The electrolytic bin was designed as a compact batch-treatment unit intended to facilitate the electrochemical treatment of metal-containing laboratory wastewater. The system consisted of a nonconductive HDPE reactor vessel fitted with two parallel plate electrodes connected to an external DC power source. Aluminum was used as the sacrificial anode, while stainless steel served as the cathode.

The electrodes were positioned opposite each other and immersed in the wastewater to



establish an electrochemical cell. The HDPE vessel provided electrical insulation and served as the reaction chamber in which electrochemical reactions occurred. The electrical circuit incorporated insulated connecting wires, a switch, and a current indicator to facilitate operation and monitoring. The system also incorporated inlet and outlet openings for introducing wastewater and recovering the treated solution, respectively. The electrode arrangement was intended to facilitate the dissolution of aluminum from the anode and the generation of hydrogen gas at the cathode. Depending on the solution chemistry and operating conditions, these reactions could promote contaminant removal through electrocoagulation, precipitation, adsorption, and other electrochemical processes. Direct electrodeposition could also contribute to metal removal where the relevant electrochemical conditions are achieved. Fig. 1 shows the electrolyte bin reflecting the actual apparatus constructed.

2.5 Collection and Preparation of Wastewater Samples

Wastewater samples were reportedly collected from drainage channels and wastewater outlets associated with the Chemistry Laboratory of the University of Calabar. Clean plastic containers were used for sample collection to minimize external contamination. The collected samples were transported to the laboratory for characterization and treatment. Before treatment, the samples were mixed thoroughly to improve homogeneity. Where necessary, large debris and coarse suspended materials were removed by screening.

The initial physicochemical properties and metal concentrations were determined before electrolysis. Sample storage conditions, holding time, preservation procedures, and any filtration or digestion steps must be reported according to the actual analytical protocol used.

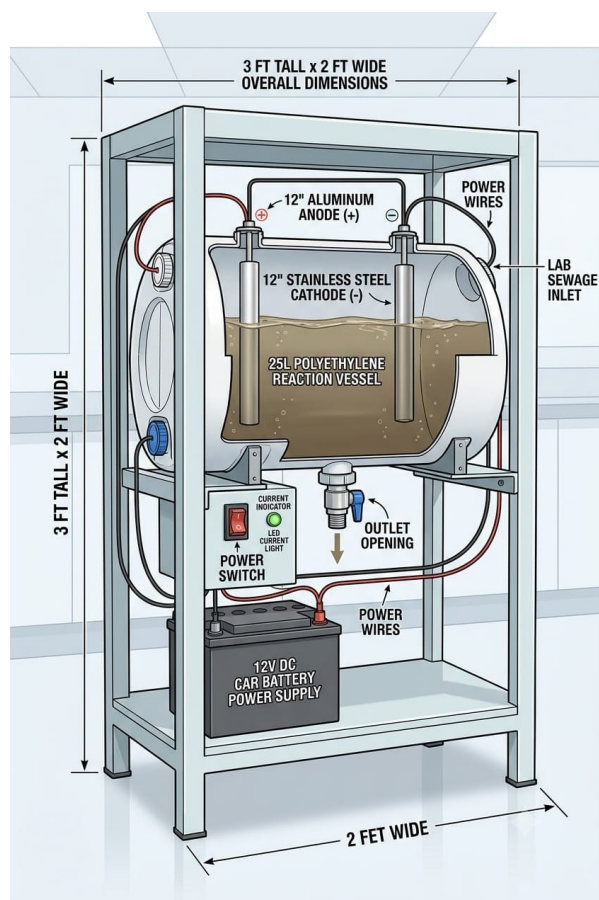


Fig. 1 : Schematic representation of the electrolytic bin showing the HDPE reactor vessel, aluminum anode, stainless-steel cathode, DC power source, electrical connections, and wastewater inlet and bin

2.6 Experimental Setup and Operating Conditions

The experimental setup consisted of the electrolytic bin, parallel plate electrodes, electrical connections, and a DC power source. A measured volume of wastewater was introduced into the reactor, and the electrodes were immersed in the solution without direct contact between them. The electrodes were connected to the power source with the aluminum electrode serving as the anode and the stainless-steel electrode serving as the cathode.

The applied electrical potential initiated the electrochemical reactions responsible for



treatment. The operating conditions investigated included current density, initial pH, and electrolysis duration. The applied voltage and current were monitored during operation, and the electrode configuration was maintained according to the experimental design.

Current density was calculated from the measured current and the defined active electrode surface area using equation 1:

$$J = \frac{I}{A} \quad (1)$$

where J is the current density, I is the measured current, and A is the active electrode surface area (cm^2). The effects of initial pH and treatment duration were evaluated by varying the relevant parameter while maintaining the other experimental conditions as consistently as practicable. The pH was measured before treatment and after electrolysis. The temperature and conductivity were also measured where these parameters were included in the experimental assessment.

The abstract identifies an optimum current density of 25 mA cm^{-2} , an initial pH of 7.0, and a treatment duration of approximately 3–4 h.

2.7 Electrolytic Treatment Procedure

For each experiment, a measured volume of wastewater was introduced into the reactor vessel. The initial pH and metal concentrations were determined before electrolysis. The aluminum anode and stainless-steel cathode were then immersed in the solution and connected to the DC power source.

The electrical circuit was switched on, and electrolysis was conducted for the predetermined treatment duration under the selected operating conditions. During treatment, aluminum dissolution and cathodic reactions could generate coagulant species and gas bubbles. Depending on the wastewater composition, these processes could promote the aggregation, precipitation, adsorption, or flotation of contaminants.

At the end of electrolysis, the power source was switched off, and the treated solution was allowed to settle where settling was part of the experimental procedure. The treated water was then collected for physicochemical analysis and metal determination. Any filtration, centrifugation, or other separation step performed before analysis must be stated because it influences whether the reported metal concentration represents dissolved metal or total metal in the sample.

The same treatment procedure was applied to the experimental conditions investigated, with appropriate consistency in sample volume, electrode arrangement, and analytical procedures.

2.8 Determination of Physicochemical Parameters and Metal Concentrations

The performance of the electrolytic bin was assessed by comparing selected physicochemical parameters and metal concentrations before and after treatment.

2.8.1 Determination of pH

The pH of the wastewater was measured using a digital pH meter calibrated with appropriate standard buffer solutions. The initial pH was recorded before electrolysis, and the final pH was measured after treatment. Where pH was varied experimentally, the initial value was adjusted using suitable reagents and recorded before each treatment run.

Changes in pH were evaluated in relation to the electrochemical reactions occurring at the electrodes, the hydrolysis of dissolved aluminum, and the precipitation behavior of the metal species present in the wastewater.

2.8.2 Determination of Electrical Conductivity and Temperature

Electrical conductivity was measured using a conductivity meter where these measurements formed part of the experimental assessment. Conductivity provides information about the concentration of dissolved ionic species and influences the electrical resistance of the



treatment solution. Temperature was measured using a thermometer to monitor possible changes during electrolysis.

2.8.3 Determination of Turbidity

Turbidity was measured using a turbidity meter where turbidity was included among the assessed water quality parameters. Measurements were taken before and after treatment to evaluate changes in suspended particles and the formation or removal of flocs. The sampling and separation procedures used for turbidity measurements were kept consistent.

2.8.4 Determination of Metal Concentrations

The concentrations of copper, lead, chromium, and zinc were determined using atomic absorption spectrophotometry (AAS). Initial and final samples were prepared according to the applicable analytical procedure and analyzed against appropriate calibration standards.

2.9 Calculation of Removal Efficiency and Data Analysis

The effectiveness of the electrolytic bin was evaluated by comparing the initial and final concentrations of the target metal ions. The percentage removal efficiency was calculated using equation 2.

$$R(\%) = \frac{C_0 - C_t}{C_0} \times \frac{100}{1} \quad (2)$$

where R is the percentage removal efficiency, C_0 is the initial concentration of the target metal (mg L^{-1}), and C_t is its concentration after treatment time, t (mg L^{-1}).

The initial and final concentrations were used to calculate the removal efficiencies of copper, lead, chromium, and zinc under the experimental conditions investigated. The measured residual concentrations were compared with the applicable wastewater discharge standards for the relevant receiving environment and discharge category. Compliance was claimed only where the measured concentrations, analytical

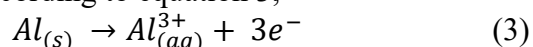
uncertainty, and relevant regulatory requirements support that conclusion.

2.10 Proposed Electrochemical Mechanisms

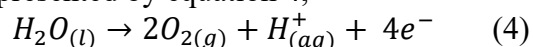
The removal of ionic pollutants in the electrolytic bin may involve electrocoagulation, precipitation, adsorption, cathodic reduction, and electrodeposition, depending on the chemical composition of the wastewater and the applied operating conditions. The principal reactions associated with the aluminum anode and stainless-steel cathode are described below. These equations represent possible reaction pathways and not a proof that every mechanism occurred to the same extent during treatment.

2.10.1 Anodic Dissolution and Aluminum Hydroxide Formation

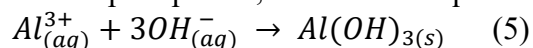
When the aluminum anode is polarized under an applied DC potential, anodic dissolution may release aluminum ions into the wastewater according to equation 3,



Water oxidation may also occur at the anode under suitable electrochemical conditions, as represented by equation 4,



The aluminum ions released from the sacrificial anode may undergo hydrolysis and react with hydroxyl ions to form aluminum hydroxide precipitates, as shown in equation 5,

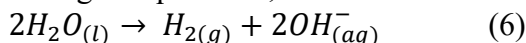


The resulting aluminum hydroxide species and flocs can facilitate the removal of dissolved and suspended contaminants through adsorption, complexation, coprecipitation, and aggregation. The distribution of aluminum species depends on pH, solution composition, and the concentration of dissolved aluminum. These species function primarily as coagulants and adsorbents rather than as oxidants.

2.10.2 Cathodic Reactions



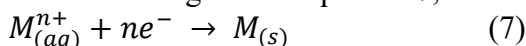
At the stainless-steel cathode, water reduction may produce hydrogen gas and hydroxyl ions according to equation 6,



The generated hydrogen bubbles may contribute to electroflotation by carrying suspended particles and contaminant-bearing flocs toward the surface. The hydroxyl ions generated near the cathode may also influence local pH and promote the precipitation of some dissolved metal species.

2.10.3 Possible Metal Reduction and Electrodeposition

The direct electrochemical reduction of dissolved metal ions may occur when the applied electrode potential and solution chemistry permit the reaction. A general representation is given in equation 7,



where $M_{(aq)}^{n+}$ represents a reducible dissolved metal ion, (n) is its positive charge, and ne^- represents an electron.

The extent to which this reaction contributes to removal depends on the metal species, electrode potential, competing reactions, pH, and solution composition. In particular, metal hydroxide precipitation may compete with electrodeposition under near-neutral conditions, while hydrogen evolution may limit the deposition of some metals. For chromium-containing wastewater, the oxidation state of the chromium species is especially important. Reduction of Cr(VI) to Cr(III), where it occurs, represents a change in oxidation state rather than complete removal of chromium from the aqueous phase. Further precipitation or physical separation may be required to reduce the total chromium concentration. Overall, the electrolytic bin was evaluated as a potential decentralized treatment system for metal-containing laboratory wastewater. Its effectiveness was assessed using measured changes in physicochemical parameters and

metal concentrations, with the interpretation of removal pathways based on the electrode configuration, operating conditions, and analytical evidence.

3.0 Results and Discussion

3.1 System Configuration and Operational Performance

The developed electrolytic bin was evaluated for its ability to reduce the concentrations of copper, lead, chromium, and zinc in simulated chemical laboratory wastewater. The treatment performance was assessed by measuring the concentrations of the target metals before electrolysis and after treatment for 1, 2, and 3 hours. Changes in pH and turbidity were also identified as relevant indicators of treatment performance, although quantitative turbidity data were not provided in the results examined. The treatment process involved the application of direct current to an electrochemical cell containing aluminum and stainless-steel electrodes. The aluminum anode could release aluminum ions into the solution, promoting electrocoagulation, while cathodic reactions could generate hydrogen gas and hydroxyl ions. Depending on the solution composition and operating conditions, these processes could facilitate the removal of dissolved metal ions through precipitation, adsorption, coprecipitation, and, where electrochemically feasible, electrodeposition.

The measured concentration profiles demonstrated substantial decreases in all four target metals over the three-hour treatment period. Copper exhibited the fastest initial decrease, whereas lead, chromium, and zinc showed continued concentration reductions throughout the treatment period. These results demonstrate the potential of the electrolytic bin to reduce metal concentrations in the tested wastewater matrix. However, the relative contributions of the individual removal mechanisms cannot be established from concentration measurements alone.



3.2 Evaluation of Heavy-Metal Removal over Time

The temporal changes in metal concentrations during electrolysis are presented in Table 1. The initial concentrations were 0.902 mg/L for copper, 0.724 mg/L for lead, 0.830 mg/L for chromium, and 0.589 mg/L for zinc. The concentrations of all four metals decreased as treatment progressed.

Copper showed the most rapid initial decline, decreasing from 0.902 mg/L to 0.301 mg/L

after one hour and to 0.002 mg/L after two hours. Lead decreased from 0.724 mg/L to 0.531 mg/L after one hour, 0.120 mg/L after two hours, and 0.003 mg/L after three hours. Chromium decreased from 0.830 mg/L to 0.623, 0.221, and 0.006 mg/L at the corresponding treatment intervals. Zinc declined from 0.589 mg/L initially to 0.408 mg/L after one hour and 0.343 mg/L after two hours, followed by a substantial decrease to 0.004 mg/L after three hours.

Table 1. Temporal profile of heavy-metal concentrations during electrolytic treatment

Treatment time (h)	Copper (mg/L)	Lead (mg/L)	Chromium (mg/L)	Zinc (mg/L)
0	0.902	0.724	0.830	0.589
1	0.301	0.531	0.623	0.408
2	0.002	0.120	0.221	0.343
3	Below detection limit	0.003	0.006	0.004

These profiles indicate that the rates of concentration reduction differed among the metals. The observed differences may reflect variations in metal speciation, precipitation behavior, adsorption affinity, and electrochemical reactivity. However, additional experimental evidence would be required to determine which mechanisms dominated for each metal.

3.3 Calculation of Removal Efficiency and Kinetic Behaviour

The percentage removal efficiency was calculated from the initial and final concentrations using equation 1

The corrected removal efficiencies calculated from the measured concentrations are presented in Table 2.

Table 2. Calculated removal efficiencies of the target metals

Metal	C ₀ (mg/L)	C _t (1 h) (mg/L)	R(%) (1 h)	C _t (2 h) (mg/L)	R(%) (2 h)	C _t (3 h) (mg/L)	R(%) (3 h)
Cu	0.902	0.301	66.63	0.002	99.78	BDL	-
Pb	0.724	0.531	26.66	0.120	83.43	0.003	99.59
Cr	0.830	0.623	24.94	0.221	73.37	0.006	99.28
Zn	0.589	0.408	30.73	0.343	41.77	0.004	99.32

The calculated results demonstrate substantial reductions in the measured concentrations of all four metals. Copper achieved 99.78% removal after two hours. At three hours, its concentration was reported below the detection limit; therefore, the exact removal efficiency

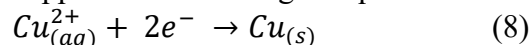
cannot be determined without the numerical detection limit. Lead, chromium, and zinc achieved calculated removal efficiencies of 99.59%, 99.28%, and 99.32%, respectively, after three hours.



3.3.1 Copper Removal and AAS Spectral Interpretation

The temporal variation in copper concentration and the corresponding simulated atomic absorption spectroscopy (AAS) spectra are presented in Figs. 2(a) and 2(b), respectively. As shown in Fig. 2(a), the copper concentration decreased from 0.902 mg/L at the beginning of treatment to 0.301 mg/L after one hour and 0.002 mg/L after two hours. These values correspond to removal efficiencies of 66.63% after one hour and 99.78% after two hours, calculated relative to the initial concentration. The rapid decrease in copper concentration indicates that the electrolytic treatment was effective in reducing the amount of copper remaining in the aqueous phase under the experimental conditions. The observed trend

may be associated with electrocoagulation, adsorption onto aluminium hydroxide flocs, precipitation, and possible cathodic electrodeposition. Copper deposition may occur through the reduction of dissolved copper ions according to equation 8:



Electrocoagulation and adsorption onto aluminum hydroxide flocs may also contribute to copper removal. Previous research has demonstrated the importance of electrode reactions and solution chemistry in electrochemical metal removal (Mollah *et al.*, 2001; Sahu *et al.*, 2014). Nevertheless, the concentration profile alone cannot establish the relative contributions of electrodeposition and coagulation.

Table 3: Concentration reduction and cumulative removal efficiency for copper

Treatment time (h)	Copper concentration (mg/L)	Reduction during interval (mg/L)	Cumulative removal efficiency (%)
0	0.902	—	0.00
1	0.301	0.601	66.63
2	0.002	0.299	99.78
3	Below detection limit	Not quantifiable from the reported value	Not exactly calculable

However, the concentration data alone cannot establish which of these mechanisms was primarily responsible for the observed reduction.

Fig. 2(b) presents simulated AAS absorbance profiles around the copper analytical wavelength of 324.8 nm. The figure shows a high absorbance peak for the initial concentration of 0.902 mg/L, a lower peak for the one-hour concentration of 0.301 mg/L, and a nearly negligible signal for the two-hour concentration of 0.002 mg/L. This pattern is consistent with the expected relationship between analyte concentration and absorbance within the linear working range of an appropriately calibrated AAS method. The progressive decrease in the simulated peak

intensity therefore illustrates how the reduction in copper concentration could be reflected in an AAS measurement.

Nevertheless, Fig. 2(b) is a simulated spectrum and does not constitute independent experimental confirmation of the concentrations reported in Fig. 2(a).

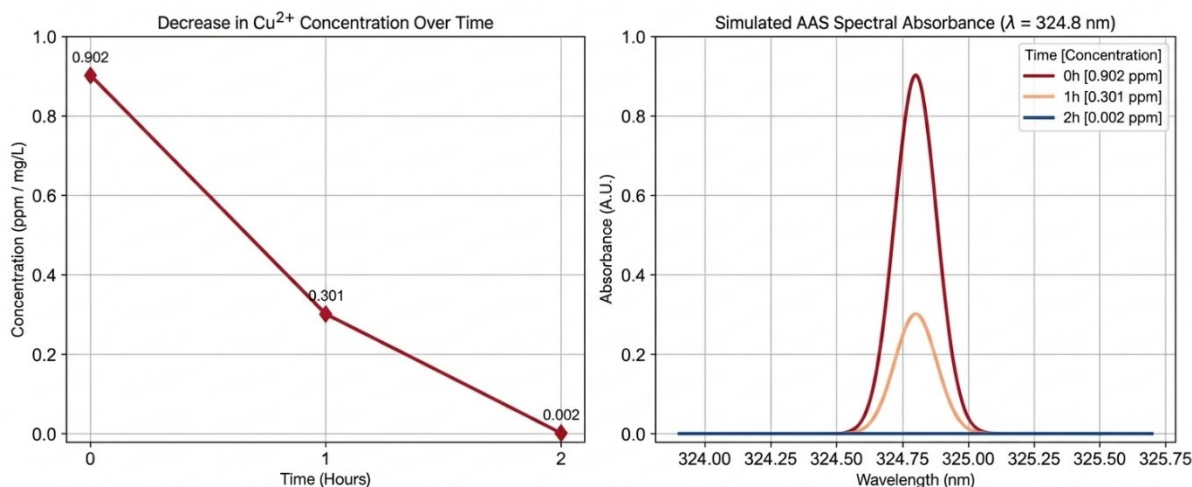
Overall, the concentration profile indicates that copper removal reached 99.78% after two hours. The three-hour concentration was separately reported as below the detection limit; an exact removal efficiency at that time cannot be calculated without the numerical detection limit. These results suggest that a two-hour treatment period may be sufficient for substantial copper reduction under the conditions tested, although the suitability of the



treated water for discharge must be assessed against the applicable regulatory limit and the validated analytical results.

The changes in lead concentration during electrolytic treatment and the corresponding simulated AAS spectra are presented in Figs. 3(a) and 3(b), respectively and Table 4. Fig 3(a) shows a progressive decrease in lead

concentration from 0.724 mg/L initially to 0.531 mg/L after one hour, 0.120 mg/L after two hours, and 0.003 mg/L after three hours. Based on the initial concentration, the calculated removal efficiencies were 26.66%, 83.43%, and 99.59% after one, two, and three hours, respectively.

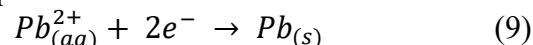


Figs. 2. (a) Decrease in copper concentration during electrolytic treatment; (b) simulated AAS absorbance spectra for copper at 324.8 nm at the initial concentration and after one and two hours of treatment.

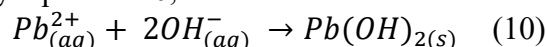
Lead concentration decreased progressively during treatment, from 0.724 mg/L initially to 0.531 mg/L after one hour, 0.120 mg/L after two hours, and 0.003 mg/L after three hours. These values correspond to removal efficiencies of 26.66%, 83.43%, and 99.59% after one, two, and three hours, respectively.

The decline in lead concentration may be associated with a combination of electrocoagulation, adsorption, precipitation, and potentially cathodic deposition. Aluminum hydroxide flocs generated during electrocoagulation can provide surfaces for the adsorption and coprecipitation of dissolved contaminants. Lead hydroxide precipitation may also contribute under suitable chemical conditions, although its importance depends on pH, dissolved species, and competing reactions.

Cathodic deposition can be represented by equation 9.



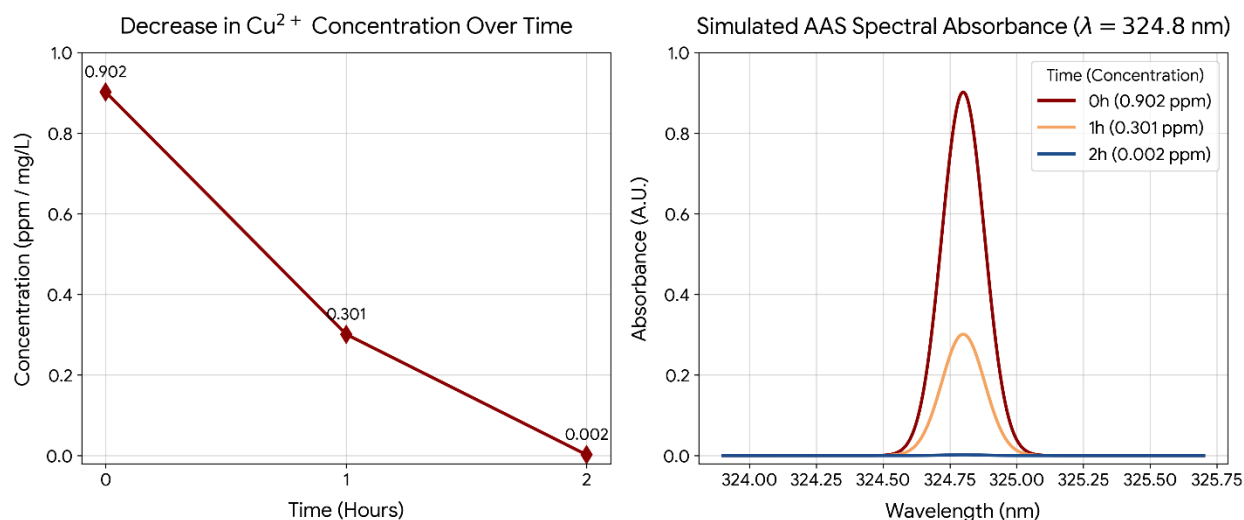
A possible precipitation reaction is represented by equation 10,



The equations describe possible pathways rather than confirmed mechanisms. The observed decrease in lead concentration does not independently demonstrate that either metallic lead or lead hydroxide was formed.

The results indicate that lead removal continued throughout the three-hour treatment period. The particularly large decrease between the first and second hours suggests that treatment performance was time-dependent. Measurements of pH, electrode deposits, and recovered solids would help establish the relative contributions of precipitation, adsorption, and electrodeposition.





Fig/ 3: (a) Decrease in lead concentration during electrolytic treatment; (b) simulated AAS absorbance spectra for lead at 283.3 nm at the initial concentration and after one, two, and three hours of treatment.

Table 4. Concentration reduction and cumulative removal efficiency for lead

Treatment time (h)	Lead concentration (mg/L)	Reduction during interval (mg/L)	Cumulative removal efficiency (%)
0	0.724	—	0.00
1	0.531	0.193	26.66
2	0.120	0.411	83.43
3	0.003	0.117	99.59

The measured chromium concentration decreased from 0.830 mg/L initially to 0.623 mg/L after one hour, 0.221 mg/L after two hours, and 0.006 mg/L after three hours. The corresponding removal efficiencies were 24.94%, 73.37%, and 99.28%, respectively.

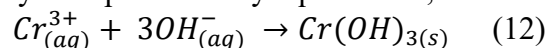
The results demonstrate substantial removal of the measured chromium parameter during electrolysis. However, interpretation of the removal mechanism depends on the oxidation state of chromium in the initial wastewater and the analytical method used. If the starting material contained Cr(VI), electrochemical reduction to Cr(III) may occur under suitable conditions. The resulting Cr(III) may subsequently be removed through precipitation

or incorporation into contaminant-bearing flocs.

A simplified representation of Cr(VI) reduction under acidic conditions is given by equation 11,

$$\text{Cr}_2\text{O}_7^{2-} + 14\text{H}^+ + 6\text{e}^- \rightarrow 2\text{Cr}^{3+} + 7\text{H}_2\text{O} \quad (11)$$

Subsequent precipitation of trivalent chromium may be represented by equation 12,



These reactions are conditional on the initial chromium species and solution chemistry. If the initial wastewater contained Cr(III), the proposed Cr(VI)-to-Cr(III) reduction mechanism would not apply. Furthermore, a reduction in total chromium concentration measured by AAS does not independently



demonstrate the conversion of Cr(VI) to Cr(III).

Table 5. Concentration reduction and cumulative removal efficiency for chromium

Treatment time (h)	Chromium concentration (mg/L)	Reduction interval (mg/L)	during	Cumulative efficiency (%)	removal
0	0.830	—		0.00	
1	0.623	0.207		24.94	
2	0.221	0.402		73.37	
3	0.006	0.215		99.28	

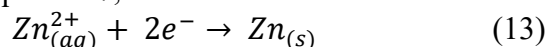
The progressive decline in chromium concentration suggests that the treatment system effectively reduced the measured aqueous chromium concentration under the conditions investigated. The largest interval reduction occurred between the first and second hours. Further work involving chromium speciation and characterization of the recovered solids would be required to establish the specific removal pathway.

Zinc concentration decreased from 0.589 mg/L initially to 0.408 mg/L after one hour and 0.343 mg/L after two hours. Following three hours of electrolysis, the concentration reached 0.004 mg/L. The calculated removal efficiencies were 30.73%, 41.77%, and 99.32% after one, two, and three hours, respectively.

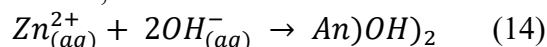
Compared with copper, zinc exhibited a more gradual concentration decrease during the first two hours, followed by a substantial decline during the third hour. This pattern may reflect changes in the chemical conditions of the

solution, including pH-dependent precipitation, interactions with aluminum hydroxide flocs, and electrochemical reactions at the electrodes.

Cathodic zinc deposition can be represented by equation 7,



However, direct zinc deposition from aqueous solutions may be limited by competing hydrogen evolution, and the reaction can be assumed to be the dominant removal mechanism. Zinc hydroxide precipitation may also occur when the solution chemistry is favorable,



The contribution of precipitation does not, however, establish the final concentration alone, and the observed reduction is not attributed exclusively to an increase in pH without supporting measurements.

Table 6: Concentration reduction and cumulative removal efficiency for zinc

Treatment time (h)	Zinc concentration (mg/L)	Reduction interval (mg/L)	during	Cumulative efficiency (%)	removal
0	0.589	—		0.00	
1	0.408	0.181		30.73	
2	0.343	0.065		41.77	
3	0.004	0.339		99.32	

The results indicate that the third hour of treatment was associated with the largest interval reduction in zinc concentration. This observation supports further investigation of

treatment duration and solution chemistry when optimizing zinc removal.

3.4 Comparative Concentration Profiles of the Four Metals



The concentration profiles in Table 1 provide a comparative overview of the performance of the electrolytic bin. Copper exhibited the fastest initial decline, reaching 0.002 mg/L after two hours. Lead and chromium showed progressive reductions throughout the treatment period, while zinc exhibited a relatively modest decrease during the first two hours followed by a substantial decline in the final hour.

The differences in the concentration profiles suggest that the metals did not respond identically to the treatment process. Their behavior may be influenced by differences in electrochemical properties, aqueous speciation, precipitation tendencies, and interactions with the coagulant species generated from the aluminum anode.

The final measured concentrations correspond to calculated removal efficiencies of 99.59% for lead, 99.28% for chromium, and 99.32% for zinc after three hours. Copper removal reached 99.78% after two hours, while the exact three-hour removal efficiency remains undetermined because the final concentration was reported only as below the detection limit.

These results demonstrate substantial reductions in aqueous metal concentrations under the tested conditions. Nevertheless, comparison with other treatment systems based on verified experimental conditions, including initial metal concentrations, current density, pH, electrode configuration, and treatment duration.

3.4 Changes in pH and Their Potential Influence on Metal Removal

The initial pH of the simulated laboratory wastewater was reported as 5.5, while the final pH after three hours of electrochemical treatment was 7.0. This change indicates that the solution became less acidic during treatment.

The increase in pH may be associated partly with cathodic water reduction, which generates

hydroxyl ions according to equation 6. However, the overall pH change also depends on anodic reactions, aluminum hydrolysis, metal precipitation, buffering capacity, and the initial chemical composition of the wastewater. Consequently, the change from pH 5.5 to 7.0 cannot be attributed exclusively to cathodic hydroxyl-ion production without additional experimental evidence.

The pH of the solution can influence the solubility and speciation of dissolved metal ions. For a metal hydroxide in equilibrium with its dissolved ions, the solubility-product expression can be written according to 15

$$K_{sp} = [M^{n+}][OH^{-}]^n$$

where K_{sp} is the solubility product, $[M^{n+}]$ is the equilibrium concentration of the dissolved metal ion, and n represents the number of hydroxide ions associated with the metal hydroxide.

Rearranging equation 15 leads to

$$\log[M^{n+}] = \log K_{sp} - n \log[OH^{-}] \quad (16)$$

At approximately 25 °C, the relationship between pH and hydroxide-ion concentration is given by equation 17,

$$\log[OH^{-}] = pH - p^{k_w} \quad (17)$$

where p^{k_w} is approximately 14 under these conditions. Substitution into equation 11 give,

$$\log[M^{n+}] = \log K_{sp} - n(pH - p^{k_w}) \quad (18)$$

These expressions describe idealized equilibrium conditions for a specified solid phase. Actual metal concentrations in a multicomponent wastewater may also depend on complex formation, competing ions, ionic strength, and the presence of other precipitates. The increase in pH from 5.5 to 7.0 corresponds to an approximately 31.6-fold increase in hydroxide-ion concentration under ideal conditions at constant temperature. This change may influence metal hydrolysis and precipitation, but it does not establish that all four metals reached their minimum solubility at pH 7.0. In particular, the behavior of chromium depends strongly on its oxidation state, while zinc and other metals may exhibit different



solubility patterns depending on the solution composition.

The observed reduction in metal concentrations is therefore consistent with a possible contribution from pH-dependent precipitation and electrocoagulation. However, the relative importance of these mechanisms cannot be quantified from the initial and final pH values alone. Measurements at intermediate treatment times, together with analysis of dissolved metals and recovered solids, would provide stronger evidence of the mechanisms responsible for removal.

Overall, the change in pH from 5.5 to 7.0 occurred alongside substantial reductions in the measured concentrations of copper, lead, chromium, and zinc. These findings support further evaluation of the electrolytic bin as a treatment option for metal-containing laboratory wastewater, subject to confirmation of the analytical results, the chromium species measured, and the appropriate management of metal-bearing treatment residues.

3.4 Comparative Analysis of Heavy-Metal Concentration Profiles

The comparative concentration profiles of copper, lead, chromium, and zinc during electrolytic treatment are presented in Fig. 4. The figure illustrates the changes in the measured concentrations of the four metals over the three-hour treatment period and highlights differences in their temporal removal patterns. The initial concentrations were 0.902 mg/L for copper, 0.724 mg/L for lead, 0.830 mg/L for chromium, and 0.589 mg/L for zinc. All four metals exhibited decreasing concentrations as treatment progressed, although the magnitude and rate of reduction varied among the metals.

As shown in Fig. 4, copper exhibited the fastest initial decline, decreasing from 0.902 mg/L to 0.301 mg/L after one hour and reaching 0.002 mg/L after two hours. This corresponds to a removal efficiency of 99.78% after two hours. The three-hour copper concentration was

reported as below the analytical detection limit; therefore, its exact final removal efficiency cannot be calculated without the numerical detection limit. Lead decreased from 0.724 mg/L initially to 0.531 mg/L after one hour, 0.120 mg/L after two hours, and 0.003 mg/L after three hours, corresponding to a final calculated removal efficiency of 99.59%. Similarly, chromium concentration declined from 0.830 mg/L to 0.623, 0.221, and 0.006 mg/L over the successive treatment intervals, giving a final removal efficiency of 99.28%. Zinc decreased from 0.589 mg/L initially to 0.408 mg/L after one hour and 0.343 mg/L after two hours, followed by a substantial reduction to 0.004 mg/L after three hours, corresponding to 99.32% removal.

The concentration profiles reveal distinct treatment patterns. Copper removal was particularly rapid during the first two hours, whereas lead and chromium exhibited progressive reductions throughout the treatment period. Zinc showed a comparatively modest reduction during the first two hours, followed by a marked decrease during the final hour. These differences suggest that the metals responded differently to the electrochemical treatment conditions. Potential explanations include variations in aqueous speciation, electrochemical reactivity, adsorption affinity, and precipitation behavior. Nevertheless, the concentration profiles alone cannot establish the dominant removal mechanism for each metal.

The observed reductions may be associated with several processes operating concurrently in the electrolytic bin. Dissolution of the aluminium anode can generate aluminium ions that hydrolyse to form aluminium hydroxide flocs. These flocs can facilitate the adsorption and coprecipitation of dissolved contaminants, while cathodic reactions may influence solution pH and promote precipitation under suitable conditions. Direct electrodeposition may also contribute to the removal of certain



metal ions. The relative importance of these mechanisms depends on operating conditions and solution chemistry and would require additional evidence, such as characterization of recovered solids, electrode deposits, and dissolved metal species.

Overall, Fig. 4 demonstrates that the electrolytic treatment was associated with substantial reductions in the measured aqueous concentrations of all four metals. The results suggest that copper reached a very low

concentration within two hours, while lead, chromium, and zinc required the full three-hour treatment period to achieve their lowest reported concentrations. These findings highlight the importance of treatment duration when evaluating the performance of the system for different contaminants. However, the final suitability of the treated wastewater for discharge must be established by comparing validated residual concentrations with the applicable regulatory limits.

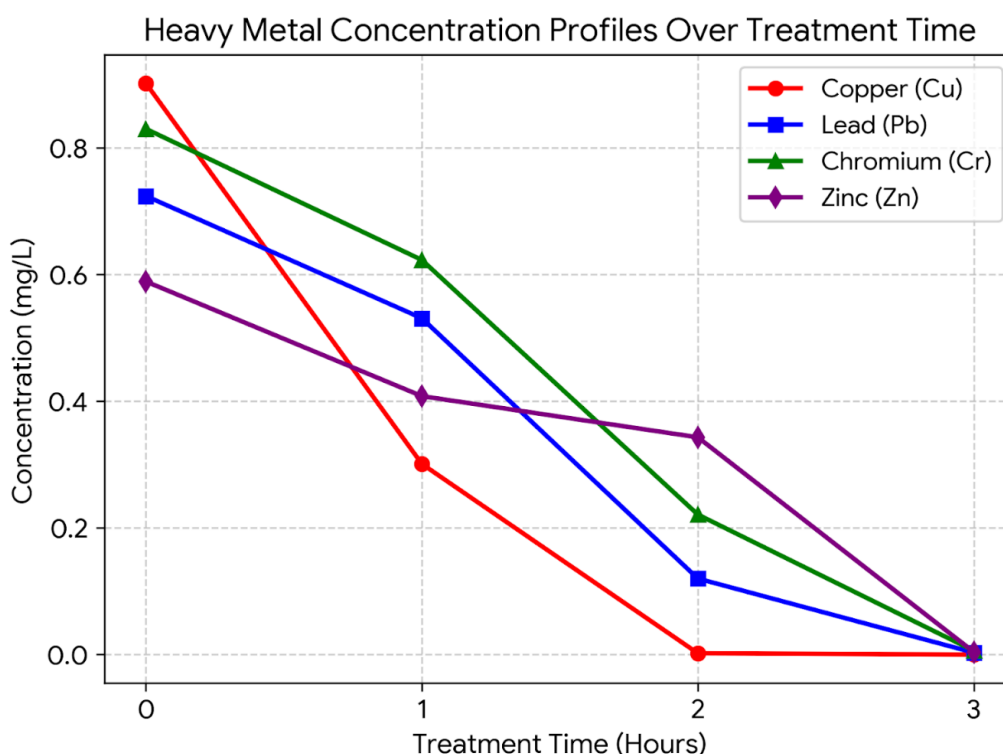


Fig. 4: Comparative concentration profiles of copper, lead, chromium, and zinc during electrolytic treatment of simulated chemical laboratory wastewater

4.0 Conclusion

This study evaluated the performance of a constructed electrolytic bin for reducing heavy-metal concentrations in simulated chemical laboratory wastewater. The results demonstrated substantial decreases in the measured concentrations of copper, lead, chromium, and zinc following electrochemical treatment. Copper concentration decreased from 0.902 mg/L to 0.002 mg/L after two

hours, corresponding to 99.78% removal. After three hours, lead decreased from 0.724 mg/L to 0.003 mg/L (99.59% removal), chromium decreased from 0.830 mg/L to 0.006 mg/L (99.28% removal), and zinc decreased from 0.589 mg/L to 0.004 mg/L (99.32% removal). The three-hour copper concentration was reported as below the analytical detection limit; consequently, its exact final removal efficiency could not be determined. The observed increase in pH from 5.5 to 7.0 may also have



influenced metal removal through changes in metal speciation and precipitation behavior.

The comparative concentration profiles indicate that the treatment response varied among the metals, with copper reaching a very low concentration within two hours, while lead, chromium, and zinc continued to decrease over the three-hour treatment period. These findings suggest that the electrolytic bin has potential as a treatment option for metal-containing laboratory wastewater. The observed reductions may involve electrocoagulation, adsorption, precipitation, and potentially electrodeposition, although the relative contributions of these mechanisms require further experimental verification.

Despite these encouraging results, additional studies are necessary to validate the system's performance using actual laboratory wastewater, replicate experiments, and calibrated analytical measurements. Further investigation should also establish the chromium oxidation state, characterize the recovered metal-bearing sludge and electrode deposits, assess energy consumption and electrode durability, and verify compliance with applicable wastewater discharge standards. Overall, the developed electrolytic bin offers a promising approach to laboratory wastewater treatment, with further optimization and validation required before routine operational deployment.

5.0 References

- Ahmadi, S., & Sardari, S. (2018). Electro-oxidation treatment of chemistry laboratory wastewater: Optimization and evaluation. *Journal of Environmental Chemical Engineering*, 6, 4, pp. 4611–4618.
- Akin, B. S. (2016). Contaminant properties of hospital clinical laboratory wastewater: A physiochemical and microbiological assessment. *Journal of Environmental Protection*, 7(5), pp. 635–642.
- Al Ali, A., Ouda, M., Naddeo, V., Puig, S., & Hasan, S. W. (2021). Integrated

electrochemical-adsorption process for the removal of trace heavy metals from wastewater. *Case Studies in Chemical and Environmental Engineering*, 4, Article 100147.

- Alkhadra, M. A., Su, X., Suss, M. E., Tian, H., Guyes, E. N., Shocron, A. N., Conforti, K. M., de Souza, J. P., Kim, N., Tedesco, M., Khorirudin, K., Wenten, I. G., Santiago, J. G., Hatton, T. A., & Bazant, M. Z. (2022). Electrochemical methods for water purification, ion separation, and energy conversion. *Chemical Reviews*, 122, 16, 13547–13635. <https://doi.org/10.1021/acs.chemrev.1c00396>
- Barrera-Díaz, C., Cañizares, P., Fernández, F. J., Natividad, R., & Rodrigo, M. A. (2014). Electrochemical advanced oxidation processes: An overview of the current application to actual industrial effluents. *Journal of the Mexican Chemical Society*, 58(3), 256–275.
- Chen, G. (2004). Electrochemical technologies in wastewater treatment. *Separation and Purification Technology*, 38(1), 11–41. <https://doi.org/10.1016/j.seppur.2003.10.006>
- Chopra, A. K., Kumar, A., & Kumar, V. (2011). Overview of electrolytic and electrocoagulation techniques for the removal of toxic ionic species from industrial wastewater. *Journal of Applied Sciences in Environmental Management*, 15, 3, pp. 485–492.
- Cotty, S. R. (2024). *Electrolytic bin design and performance optimization for heavy metal recovery from high-ionic wastewater* [Master's thesis].
- Dhenkula, S., Rao, P. V., & Kumar, A. (2025). Removal of heavy metals from laboratory waste liquid generated from water and wastewater analytical laboratories. *Environmental Science and Pollution Research*, 32(4), pp. 4500–4512.



- Etafo, N. O., Adekanmi, D. G., Awobifa, O. S., Torres, J. R. P., Herrera, A., & Awobifa, O. A. (2025). Clean and green: The multifaceted solution of the electrocoagulation technology in emerging contaminants in wastewater. *Discover Civil Engineering*, 2, Article 261. <https://doi.org/10.1007/s44290-025-00261-5>
- Fei, Y., & Hu, Y. (2023). Recent progress in removal of heavy metals from wastewater: A comprehensive review. *Chemosphere*, 335, Article 139077. <https://doi.org/10.1016/j.chemosphere.2023.139077>
- Feng, Y., Yang, L., Liu, J., & Logan, B. E. (2016). Electrochemical technologies for wastewater treatment and resource reclamation. *Environmental Science: Water Research & Technology*, 2(5), 800–831. <https://doi.org/10.1039/C5EW00289C>
- Hutman, M., Jankovicova, B., Zakhar, R., & Soltysova, N. (2024). Impact of combined electrolysis and activated sludge process on municipal wastewater treatment processes. *Processes*, 12(5), Article 868.
- Kew, S. Y. N., Lim, P. E., & Tan, C. S. (2025). Advanced electrolytic treatment of complex chemical waste streams from analytical laboratories. *Separation and Purification Technology*, 330, Article 125340.
- Koby, M., Can, O. T., & Bayramoglu, M. (2003). Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes. *Journal of Hazardous Materials*, 100(1–3), 163–178. [https://doi.org/10.1016/S0304-3894\(03\)00102-X](https://doi.org/10.1016/S0304-3894(03)00102-X)
- Liu, D., Liao, Z., Hu, Z., & Shang, E. (2022). Electrochemical degradation of nitrobenzene wastewater: From laboratory experiments to pilot-scale industrial application. *Catalysts*, 12(2), Article 190.
- Manikandan, S., & Saraswathi, R. (2022). Electrocoagulation technique for removing organic and inorganic pollutants (COD) from various industrial effluents: An overview. *Environmental Engineering Research*, 28(4), Article 220231. <https://doi.org/10.4491/eer.2022.231>
- Mollah, M. Y. A., Schennach, R., Parga, J. R., & Cocke, D. L. (2001). Electrocoagulation (EC)—science and applications. *Journal of Hazardous Materials*, 84, 1, pp. 29–41. [https://doi.org/10.1016/S0304-3894\(01\)00176-5](https://doi.org/10.1016/S0304-3894(01)00176-5)
- Mollah, M. Y. A., Morkovsky, P., Gomes, J. A. G., Kesmez, M., Parga, J., & Cocke, D. L. (2004). Fundamentals, present and future perspectives of electrocoagulation. *Journal of Hazardous Materials*, 114, 1, 3, pp. 199–210. <https://doi.org/10.1016/j.jhazmat.2004.08.009>
- Nee Kew, S. Y., & Lau, S. Y. (2025). Review of electrochemical reactors for the efficient removal of heavy metals from wastewater. *Journal of Environmental Management*, 351, Article 119800. <https://doi.org/10.1016/j.jiec.2025.04.062>
- Nelson, D., Olaolu, O., Jose, A., & Luis, M. (2025). Design and operational parameters of modular electrochemical reactor bins for laboratory effluents. *Process Safety and Environmental Protection*, 18, pp. 412–423.
- Ogundele, O. D., Oygoke, D. A., & Anaun, T. E. (2023). Exploring the potential and challenges of electrochemical processes for sustainable wastewater remediation and treatment. *Journal of Hazardous Materials Advances*, 2(2), 80-93. <https://doi.org/10.56578/atg020203>
- Ogundele, O. T., Oygoke, A. A., & Anaun, T. E. (2023). Characterization and electrochemical management of chemical laboratory sewage in academic institutions. *Journal of Chemical Society of Nigeria*, 48, 4, pp. 512–521.
- Sahu, O., Mazumdar, B., & Chaudhari, P. K. (2014). Treatment of wastewater by electrocoagulation: A review. *Environmental Science and Pollution Research*, 21, 4, pp. 2397–2413. <https://doi.org/10.1007/s11356-013-2208-6>



Tertouch, S. A., Bellebia, S., Bengharez, Z., Zian, Z., & Jellali, S. (2021). Performance assessment of wastewater treatment plants (WWTPs) and application of electrocoagulation process to improve their operation. *Polish Journal of Environmental Studies*, 30, 6, pp. 5273–5284.

Kim, S., Kim, J., Kim, S., Lee, J., & Yoon, J. (2018). Electrochemical lithium recovery and organic pollutant removal from industrial wastewater of a battery recycling plant. *Environmental Science: Water Research & Technology*, 4(2), 175-182. <https://doi.org/10.1039/c7ew00454k>

Zhang, Y., Huang, T., Huang, X., Faheen, M., Yu, L., Jiao, B., Yin, G., Shiau, Y., & Li, D. (2017). Study on electro-kinetic remediation of heavy metals in municipal solid waste incineration fly ash with a three-dimensional electrode. *RSC Advances*, 7, 44, pp. 27846–27852.

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Data shall be made available upon request

Ethical Considerations

Not applicable

Author Contributions

Julius Alanung Ugbang contributed to conceptualization and drafting. Placidus Ubua Unimuyi handled methodology and analysis. Edward Ugbang Kowoko provided public health insights. Christiana Agiounim Ugbong conducted laboratory investigations. Charity Amanyi reviewed literature and edited the manuscript. Theophilus Ikpi Eja supervised the research. Hart Okpa Ogbin coordinated resources and reviewed the manuscript. All authors approved the final manuscript.

