# Analisis Efisiensi Elektrokoagulasi dalam Penyisihan Pb, Cd, Ni, secara Simultan dalam Beberapa Kondisi pH

## *Analysis of Electrocoagulation Efficiency in the Simultaneous Removal of Pb, Cd, and Ni Under Various pH Conditions*

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**ABSTRAK**

Polusi logam berat dari aktivitas industri, seperti Pb, Cd, dan Ni, berpotensi menimbulkan efek toksik, persisten, dan bioakumulatif yang membahayakan lingkungan serta kesehatan manusia. Penelitian ini bertujuan untuk menganalisis pengaruh variasi pH terhadap efisiensi penyisihan Pb, Cd, dan Ni secara simultan menggunakan metode elektrokoagulasi, menentukan kondisi pH optimum, serta mengevaluasi konsumsi energi proses. Larutan sintetis dengan konsentrasi awal masing-masing logam sebesar 20 mg/L diolah dalam reaktor batch akrilik berkapasitas 2 L menggunakan enam elektroda aluminium dengan konfigurasi monopolar paralel. Proses elektrokoagulasi dilakukan pada tegangan 20 V, arus 4 A (26 mA/cm²), dan waktu operasi 60 menit dengan variasi pH 3, 5, 7, 9, dan 11. Konsentrasi logam dianalisis menggunakan Atomic Absorption Spectrophotometer (AAS), sedangkan COD dianalisis sesuai metode standar yang berlaku. Hasil penelitian menunjukkan bahwa variasi pH memberikan pengaruh yang signifikan terhadap efisiensi penyisihan logam berat. Kondisi optimum diperoleh pada pH 9 dengan efisiensi penyisihan Pb, Cd, dan Ni masing-masing sebesar 99,35%, 99,05%, dan 99,72%. Konsumsi energi spesifik yang diperoleh sebesar 40 kWh/m³ pada seluruh variasi pH. Hasil penelitian menunjukkan bahwa elektrokoagulasi merupakan metode yang efektif untuk penyisihan simultan logam berat Pb, Cd, dan Ni dari air limbah.

**Kata Kunci**: Elektrokoagulasi, pH, Pb, Cd, Ni

***ABSTRACT***

Heavy metal pollution originating from industrial activities, such as lead (Pb), cadmium (Cd), and nickel (Ni), poses toxic, persistent, and bioaccumulative risks that threaten both environmental quality and human health. This study aimed to investigate the effect of pH variation on the simultaneous removal efficiency of Pb, Cd, and Ni using the electrocoagulation process, to determine the optimum pH condition, and to evaluate the process energy consumption. Synthetic wastewater containing an initial concentration of 20 mg/L for each metal was treated in a 2-L acrylic batch reactor equipped with six aluminum electrodes arranged in a parallel monopolar configuration. The electrocoagulation process was conducted at a voltage of 20 V, a current of 4 A (26 mA/cm²), and an operating time of 60 minutes under varying pH conditions of 3, 5, 7, 9, and 11. Metal concentrations were analyzed using Atomic Absorption Spectrophotometry (AAS), while COD was determined according to the applicable standard analytical method. The results demonstrated that pH variation significantly affected the removal efficiency of heavy metals. The optimum condition was achieved at pH 9, resulting in removal efficiencies of 99.35% for Pb, 99.05% for Cd, and 99.72% for Ni. The specific energy consumption was 40 kWh/m³ across all pH variations. These findings indicate that electrocoagulation is an effective method for the simultaneous removal of Pb, Cd, and Ni from wastewater.

***Keywords:*** *Electrocoagulation, pH, Pb, Cd, Ni*



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## INTRODUCTION

The increasing industrial activities across various sectors, such as the metal finishing industry employing electroplating processes to improve corrosion resistance, the mining sector generating toxic tailings, and lithium-ion and lead-acid battery industries utilizing heavy metals as electrode materials, have contributed significantly to national economic growth. In addition, the paint and textile industries, which rely on synthetic pigments and dyes, have also promoted increased production and employment opportunities. However, the development of these industries has led to ecological consequences, particularly the contamination of industrial wastewater with heavy metals that are often discharged without adequate treatment. Uncontrolled wastewater disposal results in the accumulation of pollutants in aquatic and terrestrial ecosystems. Heavy metals such as lead (Pb), cadmium (Cd), and nickel (Ni) are among the major contaminants frequently detected in industrial effluents (Darwesh & Matter, 2021).

These metals are known to exhibit toxic properties because they can interfere with enzyme functions and protein structures in living organisms. Furthermore, their persistent nature makes them resistant to both chemical and biological degradation, allowing them to remain in the environment for extended periods. Pb, Cd, and Ni are also bioaccumulative, meaning that they can accumulate within aquatic food chains and be transferred from lower trophic organisms to higher-level organisms, including humans (Berlianti et al., 2025). Even at very low concentrations, below 0.1 mg/L, exposure to these heavy metals may cause severe health effects. Reported toxic effects include damage to the nervous system, which can impair cognitive and neurological functions, kidney damage that increases the risk of chronic renal failure, and reproductive disorders resulting from endocrine disruption that affects hormone regulation and fertility.

Various methods have been developed to remove heavy metals from industrial wastewater. These include adsorption processes using organic and inorganic adsorbents such as activated carbon, zeolite, and biomass, which capture metal ions through physical and chemical interactions involving van der Waals forces and coordination bonding. Other methods include ion exchange using cationic or anionic resins that replace toxic metal ions with less harmful ions such as sodium or potassium. In addition, membrane filtration technologies such as reverse osmosis and electrodialysis are widely used to separate contaminants based on pressure gradients or electrical potentials. Chemical precipitation is also commonly applied by adding reagents such as sodium sulfide or hydroxides to form insoluble precipitates that can subsequently be separated through sedimentation processes (Widyaningrum et al., 2024).

Among these methods, electrocoagulation (EC) has attracted considerable attention in recent years due to its innovative and environmentally friendly characteristics. This process generates coagulants in situ through the dissolution of sacrificial metal anodes, typically aluminum or iron, under the influence of direct electric current, thereby eliminating the need for external chemical additives. This approach not only reduces the risk of secondary pollution but also lowers long-term operational costs. The metal ions released from the anode, such as $Al^{3+}$ or $Fe^{3+}$, subsequently react with hydroxide species in water through a series of hydrolysis reactions to form amorphous hydroxide flocs characterized by high positive charge density and large specific surface area (Khan & Farooqi, 2023).

The generated hydroxide flocs play a crucial role in contaminant removal, including heavy metals such as $Pb^{2+}$, $Cd^{2+}$, and $Ni^{2+}$. The removal mechanisms involve electrostatic adsorption, coordination complexation, and coagulation-precipitation, followed by floc separation through gravitational sedimentation or flotation assisted by hydrogen bubbles generated at the cathode. Numerous studies have demonstrated the effectiveness of electrocoagulation, reporting heavy metal removal efficiencies of up to 98% under optimal conditions with relatively low energy consumption (Khan et al., 2023; Bakry, 2024).

Although the effectiveness of electrocoagulation for heavy metal removal has been widely reported, most previous studies have focused on the removal of individual metals (Bazrafshan et al., 2015). In real industrial wastewater, however, multiple heavy metals commonly coexist, creating the possibility of competitive interactions during the electrocoagulation process. These interactions may influence hydroxide species formation, adsorption onto coagulant flocs, and precipitation mechanisms, ultimately affecting the removal efficiency of each metal. Therefore, results obtained from single-metal systems may not accurately represent the performance of electrocoagulation in multi-metal systems (Bazrafshan et al., 2015).

Furthermore, studies investigating the simultaneous removal of Pb, Cd, and Ni while considering the influence of pH on removal efficiency and energy consumption remain limited. Since Pb, Cd, and Ni possess different hydrolysis constants, hydroxide solubilities, and adsorption affinities, variations in pH may result in different removal behaviors for each metal. Although the influence of pH on metal removal efficiency in multi-metal systems has been reported to be significant, studies specifically evaluating the competitive interactions among Pb, Cd, and Ni within a single electrocoagulation system are still scarce (Un & Ocal, 2015). Consequently, a research gap exists regarding the limited understanding of how pH affects the competitive interactions of Pb, Cd, and Ni in multi-metal electrocoagulation systems and the resulting impact on process energy consumption.

## MATERIALS AND METHODS

This study utilized various pieces of equipment, including a direct current (DC) power supply, a reactor measuring 15 × 15 × 12 cm, six aluminum electrodes measuring 15 × 12 cm, two 500-mL beakers, three 250-mL Erlenmeyer flasks, two droppers, an analytical balance, three 1000-mL graduated cylinders, a spatula, a pH meter, an Atomic Absorption Spectrophotometer (AAS), and COD analysis equipment in accordance with SNI 6989.2:2019. The materials used in this study included distilled water, HCl, NaOH, $Ni(NO_3)_2 \cdot 6H_2O$, $Cd(NO_3)_2 \cdot 4H_2O$, and $Pb(NO_3)_2$, with an initial concentration of 20 mg/L for each metal.

Three categories of variables were employed in this study, namely controlled variables, independent variables, and dependent variables. The controlled variables included the initial concentrations of Pb, Cd, and Ni (20 mg/L each), solution volume (2 L), aluminum electrode type, current intensity of 4 A (26 mA/cm$^2$), voltage of 20 V, treatment time of 60 minutes, six electrode plates, and an inter-electrode distance of 1.5 cm. By maintaining these parameters constant throughout the experiments, the effect of pH variation on the performance of the electrocoagulation process could be evaluated more accurately.

The independent variable in this study was the initial pH of the solution, namely pH 3, 5, 7, 9, and 11. The pH variation was selected because it is one of the most important factors affecting metal speciation, hydroxide floc formation, and contaminant removal efficiency during the electrocoagulation process. These pH conditions were applied to determine the optimum pH for the simultaneous removal of Pb, Cd, and Ni.

The dependent variables included the removal efficiencies of Pb, Cd, and Ni, the final concentrations of heavy metals after electrocoagulation, changes in Chemical Oxygen Demand (COD), and electrical energy consumption. These parameters are commonly used as indicators for evaluating the effectiveness and efficiency of electrocoagulation processes in the treatment of wastewater containing both inorganic and organic contaminants (Bazrafshan et al., 2015; Naje et al., 2021).

Metal removal efficiency was calculated using the following equation:

$$\mathbf{EP}\ (\%) = \frac{C_0 - C_t}{C_0}\, x\ \mathbf{100} \qquad \mathbf{(1)}$$

Where $C_0$ is the initial metal concentration (mg/L), and $C_t$ is the final metal concentration after the electrocoagulation process (mg/L).

$$\mathbf{EC} = \frac{U\ x\ I\ x\ t}{V} \qquad \mathbf{(2)}$$

EC is the electrical energy consumption ($kWh/m^3$), U is the voltage (V), I is the electric current (A), t is the process time (hours), and V is the volume of the treated solution ($m^3$). In addition, electrode mass loss is determined from the difference between the electrode mass before and after the electrocoagulation process. These parameters are used to evaluate the performance of the electrocoagulation process at each applied pH variation.

**The reactor used**

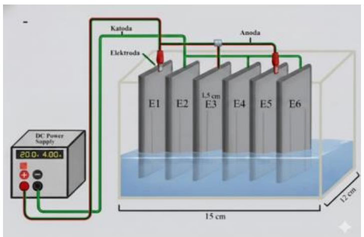


**Figure 1**. Diagram of the Electrocoagulation Process Equipment

The main equipment used is an electrocoagulation reactor made of an acrylic container with a working volume of 2 liters, operated in batch mode for each pH variation. Acrylic was selected because it is inert to the solution, meaning it does not react with the studied system, and it also facilitates visual observation during the process (Mollah et al., 2019).

The electrodes consist of six aluminum plates arranged in a parallel monopolar configuration with a spacing of 1.5 cm between electrodes. Aluminum was chosen because it can generate hydroxide coagulants in situ, which are effective for removing heavy metals from solution. The electrocoagulation system is operated using a direct current (DC) power supply under constant conditions, namely a voltage of 20 V and a current of 4 A, to ensure that the electrolysis process runs stably and optimally (Naje et al., 2019).

**Research Procedure**

The research began with the preparation of an artificial solution containing the heavy metals Pb, Cd, and Ni. Each compound was weighed using an analytical balance with 0.06 g of Pb, 0.11 g of Cd, and 0.19 g of Ni to obtain a concentration of 20 mg/L, then dissolved in 2 liters of distilled water and stirred until homogeneous. Next, the pH of the solution was adjusted to pH variations of 3, 5, 7, 9, and 11 using a pH meter. Adjustments were made by gradually adding HCl solution for acidic conditions and NaOH for basic conditions until the target pH was reached and stable. The next stage was the preparation of the electrocoagulation apparatus. Aluminum electrodes functioning as anode and cathode were weighed to obtain the initial mass. A 2-liter acrylic reactor was filled with a mixed metal solution, then six aluminum electrodes were arranged in parallel with a distance of 1.5 cm between the electrodes and a submerged surface area of 10 cm × 15 cm. The electrodes were connected to a DC power supply and operated at 20 V and 2 A for 60 minutes. After the process was completed, the power button was turned off and the final pH of the solution was measured. The sample was then left for 15–60 minutes to allow the floc to settle. The clear solution was separated and stored for further analysis. The electrodes were cleaned, dried, and weighed again to determine the final mass of aluminum. Analysis was carried out on COD parameters as well as the final concentrations of Pb, Cd, and Ni using Atomic Absorption Spectrophotometry (AAS) according to standard laboratory procedures. (Kobya et al., 2020)

## RESULTS AND DISCUSSION

Based on the research results, pH variation has a significant effect on the removal efficiency of heavy metals Pb, Cd, and Ni simultaneously using the electrocoagulation process. The effect of pH can be observed through changes in the percentage of removal efficiency. In this study, the initial concentration of each metal was 20 mg/L, with a current density of 26 mA/cm², a voltage of 20 V, and an operating time of 60 minutes. In addition to metal removal efficiency, COD and energy consumption parameters were also used to evaluate the performance of the electrocoagulation process.

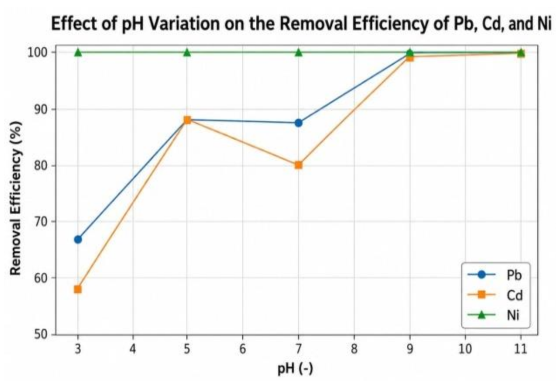


**Figure 2.** Graph of pH Analysis Results on the Electrocoagulation Process

Based on Figure 2, the removal efficiency of heavy metals tends to increase with rising pH. At pH 3, the removal efficiencies of Pb, Cd, and Ni were 66.70%, 57.90%, and 99.85%, respectively. The low removal efficiencies of Pb and Cd under acidic conditions indicate that the formation of aluminum hydroxide flocs has not occurred optimally. At low pH, $Al^{3+}$ ions predominantly exist in dissolved form, resulting in a limited amount of $Al(OH)_3$ flocs that act as adsorbents and coagulants. Consequently, the adsorption and precipitation processes of heavy metals become less effective.

At pH 5, a significant increase in removal efficiency was observed, reaching 87.70% for Pb, 87.75% for Cd, and 99.78% for Ni. This condition indicates that increasing pH promotes the formation of more stable hydroxide flocs, thereby improving metal removal performance. However, at pH 7, the removal efficiencies of Pb and Cd slightly decreased to 86.95% and 79.70%, respectively, while Ni removal remained high at 99.76%. This decline is likely due to competitive adsorption among metal ions in the multimetal system, where some active sites on the flocs cannot be optimally utilized by all metal ions simultaneously.

The optimum condition was obtained at pH 9, with removal efficiencies of 99.35% for Pb, 99.05% for Cd, and 99.72% for Ni. At this pH, the formation of $Al(OH)_3$ flocs occurs at a maximum level, enabling adsorption, charge neutralization, and heavy metal precipitation to proceed more effectively. In addition, under mildly alkaline conditions, the hydroxides of Pb, Cd, and Ni exhibit lower solubility, making them more easily precipitated and trapped within the formed flocs. These results indicate that pH 9 is the most effective condition for the simultaneous removal of the three heavy metals in the electrocoagulation system.

At pH 11, the removal efficiency remains very high, at 99.35% for Pb, 99.40% for Cd, and 99.83% for Ni.

However, the improvement compared to pH 9 is relatively minor, indicating that further increases in alkalinity do not significantly enhance performance. Under strongly alkaline conditions, the formation of more soluble hydroxo-complex species may occur, meaning that increasing pH beyond this point does not necessarily lead to proportional improvements in removal efficiency.

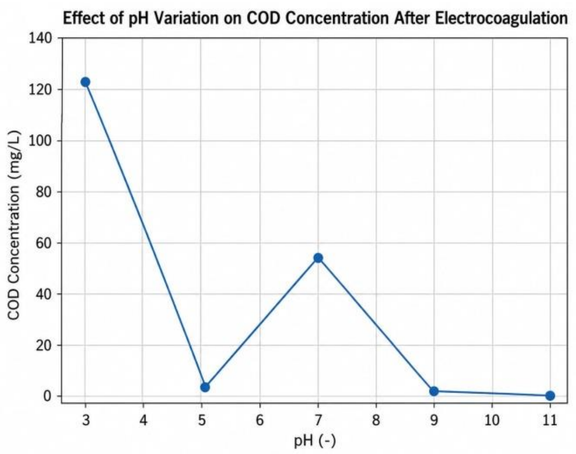


**Figure 3.** Graph of COD Analysis Results on the Electrocoagulation Process under Several pH Conditions

The decrease in COD levels also shows a trend consistent with the increase in metal removal efficiency. Based on the measurement results, the COD values after electrocoagulation decreased from 122 mg/L at pH 3 to 4 mg/L at pH 5, 54 mg/L at pH 7, 2 mg/L at pH 9, and reached 0 mg/L at pH 11. These results indicate that the electrocoagulation process is not only effective in removing heavy metals, but also capable of reducing pollutant content measured as COD through adsorption mechanisms and binding to the hydroxide flocs formed.

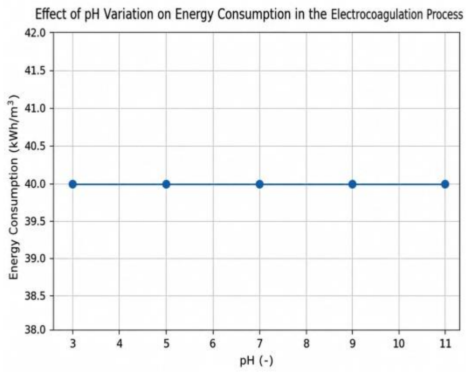


**Figure 4.** Graph of Energy Consumption

The specific energy consumption obtained in this study was 40 kWh/m³ for all pH variations. This value was calculated based on an operating voltage of 20 V, a current of 4 A, a process time of 60 minutes, and a solution volume of 2 L. Since all operating parameters were kept constant throughout the study, the energy consumption at each pH variation was also relatively similar. Therefore, the differences in removal efficiency observed at each pH were more influenced by variations in chemical mechanisms and floc formation rather than by changes in electrical energy requirements.

Overall, the results of this study indicate that pH variation is an important factor affecting the performance of electrocoagulation in the simultaneous removal of Pb, Cd, and Ni. Based on the obtained metal removal efficiencies, the optimum condition was identified at pH 9, with removal efficiencies of 99.35% for Pb, 99.05% for Cd, and 99.72% for Ni, and an energy consumption of 40 kWh/m³. These results demonstrate that electrocoagulation has strong potential as an effective method for treating industrial wastewater containing mixed heavy metals.

## CONCLUSION

Based on the results of the study, pH variation was proven to have a significant effect on the removal efficiency of heavy metals Pb, Cd, and Ni simultaneously using the electrocoagulation process. An increase in pH from acidic to alkaline conditions enhanced the formation of $Al(OH)_3$ flocs, which play a key role in the adsorption, coagulation, and precipitation mechanisms of heavy metals. The highest simultaneous removal efficiencies were obtained at pH 9, with removal efficiencies of 99.35% for Pb, 99.05% for Cd, and 99.72% for Ni. These results indicate that moderately alkaline conditions provide the most favorable environment for the formation of stable hydroxide flocs that effectively remove heavy metals from the solution.

The study also showed that pH variation did not significantly affect the energy consumption of the electrocoagulation process. Under all tested pH conditions, the specific energy consumption remained relatively constant at 40 $kWh/m^3$ because voltage, current, operating time, and solution volume were kept constant throughout the experiments. Therefore, the differences in removal efficiency were more influenced by changes in chemical and electrochemical mechanisms at each pH condition rather than by variations in energy demand.

These findings suggest that the electrocoagulation process has strong potential to be applied as a wastewater treatment method for industrial effluents containing mixed heavy metals such as Pb, Cd, and Ni. Operation at pH 9 achieves very high removal efficiency without increasing energy consumption, making it an effective and economical operating condition for sustainable wastewater treatment. This study also provides a scientific basis for the development and upscaling of electrocoagulation systems to meet applicable wastewater quality standards.

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