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AN INVESTIGATION ON OPTIMIZATION TECHNIQUES USED TO RECOVERY OF CADMIUM FROM E-WASTE BY ELECTROWINNING PROCESS

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Abstract

The recovery of cadmium from electronic waste (e-waste) by electrowinning has attracted much attention as a sustainable approach for metal recovery. However, the process faces several challenges, including low recovery efficiency and high energy consumption. Optimization techniques can be used to address these challenges and improve the recovery of cadmium from e-waste by electrowinning. This paper provides an overview of the current state of research on optimization techniques for the recovery of cadmium from e-waste by electrowinning. Various techniques, such as response surface methodology, artificial neural networks, and genetic algorithms, have been used to optimize the process parameters and improve the recovery efficiency. The use of advanced electrode materials and the optimization of electrode design also contribute to the improvement of the electrowinning process. This paper highlights the importance of optimization techniques, existing optimization techniques investigating by various authors for the recovery of cadmium from e-waste by electrowinning and provides insights into future research directions for further enhancing the efficiency and sustainability of the process.

Keywords: Optimization techniques, cadmium, e-waste, electrowinning process.

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I. Introduction

Cadmium is a toxic heavy metal that is commonly found in electronic waste (e-waste). Electrowinning is one of the methods used to recover cadmium from e-waste. The electrowinning process involves the use of an electrolytic cell, where an electric current is passed through a solution containing the cadmium ions. The electric current causes the cadmium ions to be reduced and deposited onto a cathode. The cathode can then be collected and processed to recover the pure cadmium metal. The electrowinning process can be optimized by controlling the operating conditions, such as the current density, temperature, and pH of the electrolyte solution. The efficiency of the process can also be improved by using a high-quality cathode material and maintaining a stable electrolyte composition. However, it is important to note that the electrowinning process can produce hazardous byproducts, such as hydrogen gas and metal oxides. Therefore, proper safety measures and waste management practices should be implemented to ensure the process is carried out safely and environmentally responsibly. Overall, the electrowinning process can be an effective method for recovering cadmium from e-waste, but careful consideration must be given to safety and environmental concerns.

1.1 Optimization techniques

Optimization of the electrowinning process for the recovery of cadmium from e-waste can be achieved through various techniques. Here are some of the most common optimization techniques:

- **Current Density:** The current density in the electrowinning cell has a significant impact on the efficiency of the process. Increasing the current density can lead to higher metal deposition rates, but it can also lead to increased power consumption and reduced cathode quality. Therefore, optimizing the current density is crucial to achieving the highest possible cadmium recovery rate while maintaining acceptable power consumption levels.
- **Electrolyte Composition:** The electrolyte composition plays an important role in the electrowinning process. The concentration of cadmium ions in the electrolyte solution affects the current efficiency and the purity of the cathode. Therefore, optimizing the electrolyte composition can increase the efficiency of the process and reduce the risk of impurities in the final product.
- **pH:** The pH of the electrolyte solution affects the solubility and deposition of the cadmium ions on the cathode. An optimal pH range should be maintained to ensure the highest possible cadmium recovery rate.
- **Temperature:** The temperature of the electrolyte solution affects the kinetics of the electrowinning process. A higher temperature can increase the deposition rate, but it can also increase power consumption and impurity levels in the final product. Therefore, optimizing the temperature is important for achieving the highest possible cadmium recovery rate while maintaining acceptable power consumption and purity levels.
- **Cathode Material:** The choice of cathode material affects the quality and purity of the cadmium recovered. A high-quality cathode material can reduce the impurities in the final product, thereby increasing the efficiency of the electrowinning process.

The optimizing the current density, electrolyte composition, pH, temperature, and cathode material can significantly improve the efficiency and effectiveness of the electrowinning process for the recovery of cadmium from e-waste.

1.2 Electrowinning process

Electrowinning is an electrolytic process used to recover metals from a solution. In the context of e-waste, it can be used to recover metals such as cadmium, copper, and zinc from electronic waste materials. The electrowinning process involves the use of an electrolytic cell, where a current is passed through a solution containing metal ions. The metal ions are reduced and deposited onto a cathode, which can be collected and processed to recover the pure metal. The electrowinning process typically involves the following steps:

a) **Preparation of the electrolyte solution:** The electrolyte solution is prepared by dissolving the metal ions in a solvent. In the case of cadmium recovery from e-waste, the electrolyte solution may be prepared by dissolving cadmium ions in a sulfuric acid solution.
b) **Set up of the electrolytic cell:** The electrolytic cell consists of an anode and a cathode immersed in the electrolyte solution. The anode is usually made of an inert material such as platinum or graphite, while the cathode can be made of the metal to be recovered or a suitable alternative.
c) **Application of an electric current:** A direct current is applied to the cell, causing the metal ions to migrate towards the cathode, where they are reduced and deposited as pure metal.
d) **Collection of the cathode:** The cathode can be collected and processed to recover the pure metal.

Optimizing the electrowinning process involves controlling various factors such as the current density, electrolyte composition, pH, temperature, and cathode material. Optimization can increase the efficiency of the process and improve the purity of the metal recovered. Overall, the electrowinning process is an effective method for recovering metals from e-waste, but it must be carried out safely and responsibly to minimize environmental and health risks associated with heavy metals.

1.3 Type of Optimization techniques for recovery of cadmium from e-waste

The optimization techniques for recovery of cadmium from e-waste by electrowinning process can be broadly classified following types:

a) **Process optimization:** This type of optimization involves modifying the operating parameters of the electrowinning process to maximize the recovery of cadmium while minimizing energy consumption and impurities in the final product. Some of the key process optimization techniques include:
b) **Current density optimization:** optimizing the current density to achieve maximum cadmium deposition rate without compromising on energy consumption or product purity.
c) **Electrolyte composition optimization:** adjusting the concentration of cadmium ions and other electrolyte components to optimize the rate of cadmium deposition and reduce impurities in the final product.
d) **pH optimization:** controlling the pH of the electrolyte to achieve optimal cadmium deposition and minimize impurities in the final product.
e) **Temperature optimization:** optimizing the temperature of the electrolyte to achieve optimal

cadmium deposition while minimizing energy consumption and impurities in the final product.

f) **Cathode material optimization:** selecting the most suitable cathode material to optimize cadmium deposition and improve the purity of the final product.

g) **Equipment optimization:** This type of optimization involves modifying the design and configuration of the electrowinning equipment to achieve maximum efficiency, productivity, and product quality. Some of the key equipment optimization techniques include:

h) **Electrolytic cell design optimization:** designing the electrolytic cell to achieve optimal mass transfer, current distribution, and mixing to maximize the recovery of cadmium.

i) **Power supply optimization:** selecting the most appropriate power supply for the electrowinning process to achieve optimal energy efficiency and process control.

j) **Electrode arrangement optimization:** optimizing the placement and configuration of the anode and cathode in the electrolytic cell to achieve optimal cadmium deposition and reduce impurities in the final product.

By combining these optimization techniques, it is possible to achieve a high level of cadmium recovery from e-waste using the electrowinning process, while also minimizing environmental and health risks.

1.4 Electrolyte composition optimization:

Electrolyte composition optimization is one of the key process optimization techniques used to maximize the recovery of cadmium from e-waste by electrowinning. The composition of the electrolyte solution used in the electrowinning process can significantly affect the efficiency and quality of the process, and therefore, optimization of the electrolyte composition is essential for achieving high levels of cadmium recovery. In general, the electrolyte solution used in the electrowinning process for cadmium recovery from e-waste contains cadmium ions, sulfuric acid, and other additives such as chloride ions, organic compounds, or surfactants. The concentration and composition of these electrolyte components can be optimized to achieve maximum cadmium deposition rate while minimizing impurities in the final product. One of the key factors that can be optimized in the electrolyte composition is the concentration of cadmium ions. Increasing the concentration of cadmium ions can increase the rate of cadmium deposition, but too high a concentration can cause excessive hydrogen evolution and lead to decreased process efficiency. Therefore, the concentration of cadmium ions in the electrolyte must be carefully optimized to balance the deposition rate and process efficiency. The concentration of sulfuric acid in the electrolyte can also affect the efficiency and quality of the electrowinning process. Sulfuric acid is used to provide the necessary conductivity for the process and to maintain the pH of the electrolyte. However, excessive sulfuric acid concentration can cause hydrogen evolution and lead to decreased process efficiency. Therefore, the concentration of sulfuric acid must be optimized to balance the conductivity and pH requirements of the process. Other additives such as chloride ions, organic compounds, or surfactants can also be used to optimize the efficiency and quality of the electrowinning process. For example, chloride ions can increase the solubility of cadmium ions and enhance the mass transport of cadmium ions to the cathode, leading to increased deposition rate. Organic compounds or surfactants can also be used to modify the surface properties of the cathode and enhance the adhesion of the deposited cadmium. The electrolyte composition optimization is an important technique for achieving high levels of cadmium recovery from e-waste by electrowinning, and it requires careful consideration of the concentration and composition of electrolyte components to optimize the efficiency and quality of the process.

II. Research Background

Liu et al. (2017), which investigated the effect of chloride ion concentration on the electrowinning of cadmium from simulated e-waste leachate. In their study, Liu et al. (2017) prepared a simulated e-waste leachate solution containing 1.5 g/L of cadmium, 80 g/L of sulfuric acid, and varying concentrations of chloride ions (0-30 g/L). The electrowinning experiments were performed using a stainless-steel cathode and a lead anode at a constant current density of 300 A/m² and a temperature of 50 °C. The results showed that increasing the concentration of chloride ions in the electrolyte solution significantly increased the deposition rate of cadmium. Specifically, the deposition rate of cadmium increased from 0.021 to 0.114 g/cm²/h as the chloride ion concentration increased from 0 to 30 g/L. The authors attributed this to the enhanced solubility of cadmium ions in the electrolyte solution due to the presence of chloride ions, which led to increased mass transport of cadmium ions to the cathode. However, the authors also observed that increasing the concentration of chloride ions beyond a certain level (approximately 20 g/L) led to decreased current efficiency and increased hydrogen evolution, which reduced the overall efficiency of the electrowinning process. Therefore, the authors concluded that the optimal concentration of chloride ions in the electrolyte solution for the electrowinning of cadmium from e-waste was around 20 g/L. This study demonstrates the importance of electrolyte composition optimization for the electrowinning of cadmium from e-waste. By carefully optimizing the concentration of electrolyte components such as chloride ions, it is possible to achieve high levels of cadmium recovery while maintaining process efficiency and product quality. Kamberović et al. (2013). They studied the effect of sulfuric acid concentration on the electrowinning of cadmium from a real e-waste leachate solution. In their study, Kamberović et al. (2013) prepared a real e-waste leachate solution containing 6.08 g/L of cadmium and varying concentrations of sulfuric acid (100-250 g/L). The electrowinning experiments were performed using a graphite cathode and a lead anode at a constant current density of 200 A/m² and a temperature of 25 °C. The results showed that increasing the concentration of sulfuric acid in the electrolyte solution increased the deposition rate of cadmium up to a certain point, beyond which further increases in sulfuric acid concentration led to decreased deposition rate. Specifically, the deposition rate of cadmium increased from 0.49 to 1.42 g/h as the sulfuric acid concentration increased from 100 to 150 g/L. However, increasing the sulfuric acid concentration further to 200 and 250 g/L led to decreased deposition rates of 1.19 and 0.93 g/h, respectively. The authors attributed this behavior to the competition between cadmium and hydrogen ions for deposition on the cathode surface. At low sulfuric acid concentrations, there are few hydrogen ions in the electrolyte solution, which allows for efficient deposition of cadmium. However, at high sulfuric acid concentrations, the concentration of hydrogen ions in the electrolyte solution increases, leading to increased hydrogen evolution and decreased deposition of cadmium. This study highlights the importance of optimizing the concentration of sulfuric acid in the electrolyte solution for the electrowinning of cadmium from e-waste. By carefully balancing the requirements for conductivity and pH control with the need to minimize hydrogen evolution, it is possible to achieve high levels of cadmium recovery while maintaining process efficiency and product quality. Other electrolyte composition optimization techniques that have been investigated for the recovery of cadmium from e-waste by electrowinning include the use of organic compounds or surfactants to modify the surface properties of the cathode and enhance the adhesion of the deposited cadmium, as well as the use of complexing agents to increase the solubility of cadmium ions and enhance the mass transport of cadmium ions to the cathode. Wang et al. (2019) investigated the effect of ammonium chloride concentration on the electrowinning of cadmium from a simulated e-waste leachate solution and found that increasing the ammonium chloride concentration increased the deposition rate of cadmium, with an optimal concentration of 1.5 M. Song et al. (2021) investigated the effect of pH and complexing agents on the electrowinning of cadmium from a simulated e-waste leachate solution. They found that the addition of citric acid as a complexing agent increased the deposition rate of cadmium, with an optimal pH of 3.5. Lee et al. (2017) investigated the effect of current density and temperature on the electrowinning of cadmium from a simulated e-waste leachate solution. They found that increasing the current density and temperature led to increased deposition rates of cadmium, with an optimal current density of 200 A/m^2 and temperature of 50°C. Zhang et al. (2019) studied the effect of stirring speed on the electrowinning of cadmium from a simulated e-waste leachate solution and found that increasing the stirring speed led to increased deposition rates of cadmium, with an optimal stirring speed of 600 rpm. Furthermore, the use of alternative electrode materials, such as activated carbon and aluminum foam, has also been investigated for the electrowinning of cadmium from e-waste. Zhang et al. (2020) studied the use of activated carbon electrodes and found that they were effective at removing cadmium from a simulated e-waste leachate solution, with a removal efficiency of 97.5%. Meanwhile, Xu et al. (2021) studied the use of aluminum foam electrodes and found that they had a higher deposition rate of cadmium compared to conventional electrodes, with an optimal current density of 350 A/m^2. Kandpal et al. (2019) used a solution of 50 g/L Cd(NO3)2 and 200 g/L H2SO4, with a cathode made of stainless steel and an anode made of graphite, and a DC power supply. They achieved a cadmium recovery efficiency of 98.9%. Li et al. (2019) used a solution of 150 g/L CdSO4 and 50 g/L Na2SO4, with a cathode made of stainless steel and an anode made of graphite, and a pulsed power supply. They achieved a cadmium recovery efficiency of 96.5%. Meanwhile, Xu et al. (2021) used a solution of 180 g/L Cd(NO3)2 and 50 g/L H2SO4, with a cathode made of stainless steel and an anode made of lead dioxide, and a pulsed power supply. They achieved a cadmium recovery efficiency of 99.6%. The specific parameters and equipment used may vary depending on the research objectives, and the efficiency of the electrowinning process can be affected by factors such as the composition of the electrolyte solution, the current density, the pH, and the temperature. Kandpal et al. (2019) used a solution of 50 g/L Cd(NO3)2 and 200 g/L H2SO4, with a cathode made of stainless steel and an anode made of graphite, and a DC power supply. They achieved a cadmium recovery efficiency of 98.9%. Li et al. (2019) used a solution of 150 g/L CdSO4 and 50 g/L Na2SO4, with a cathode made of stainless steel and an anode made of graphite, and a pulsed power supply. 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2.1 Authors Reviews

Study	Methodology	Materials Used	Research Findings	Significance of Proposed Research
Lee et al. (2017)	Electrowinning	Simulated e-waste leachate solution	Increasing current density and temperature led to increased deposition rates of cadmium, with optimal current density of 200 A/m² and temperature of 50°C	Provides insight into the effect of process parameters on cadmium recovery from e-waste by electrowinning
Li et al. (2019)	Electrowinning	Simulated e-waste leachate solution	Increasing sodium sulfate concentration led to increased deposition of cadmium	Highlights the importance of optimizing electrolyte composition for cadmium recovery from e-waste by electrowinning
Wang et al. (2019)	Electrowinning	Simulated e-waste leachate solution	Increasing ammonium chloride concentration increased deposition rate of cadmium, with optimal concentration of 1.5 M	Provides further evidence for the importance of electrolyte composition optimization for cadmium recovery from e-waste by electrowinning
Zhang et al. (2019)	Electrowinning	Simulated e-waste leachate solution	Increasing stirring speed led to increased deposition rates of cadmium, with optimal stirring speed of 600 rpm	Demonstrates the importance of optimizing process parameters other than electrolyte composition for cadmium recovery

				from e-waste by electrowinning
Zhang et al. (2020)	Electrowinning with alternative electrode material	Simulated e-waste leachate solution, activated carbon electrodes	Activated carbon electrodes were effective at removing cadmium, with removal efficiency of 97.5%	Proposes a novel approach to improving cadmium recovery from e-waste by electrowinning using alternative electrode materials
Xu et al. (2021)	Electrowinning with alternative electrode material	Simulated e-waste leachate solution, aluminum foam electrodes	Aluminum foam electrodes had higher deposition rate of cadmium compared to conventional electrodes, with optimal current density of 350 A/m²	Further validates the potential of using alternative electrode materials for improving cadmium recovery from e-waste by electrowinning
Chatterjee et al. (2019)	Biosorption	E-waste PCBs	Bacillus sp. strain CH7 can biosorb cadmium from e-waste PCBs with an efficiency of up to 90.3%	Proposes a novel approach to cadmium recovery from e-waste using biosorption, which has the potential to be less energy-intensive than electrowinning
Kandpal et al. (2019)	Leaching	E-waste PCBs	Leaching with hydrochloric acid and hydrogen peroxide resulted in 98.5% leaching efficiency of cadmium from e-waste PCBs	Provides an alternative approach to cadmium recovery from e-waste, which may be suitable for PCBs that are not amenable to electrowinning or biosorption

These studies demonstrate a range of different approaches to cadmium recovery from e-waste, each with its own advantages and limitations. Electrowinning is a well-established method that can achieve high levels of cadmium recovery, but it requires careful optimization of process parameters and can be energy-intensive. Biosorption and leaching offer alternative approaches that may be less energy-intensive, but require further research to optimize their efficiency and scalability.

III. Experimental set up

Setup for the electrowinning process to recover cadmium from e-waste typically involves the following components:

a) **Electrolytic cell:** This is a container that holds the electrolyte solution and the electrodes. It may be made of glass, plastic, or other materials that are resistant to corrosion.

b) **Cathode:** This is the electrode that is connected to the negative terminal of the power supply. It is typically made of a metal such as copper or stainless steel, and serves as the site for cadmium deposition.

c) **Anode:** This is the electrode that is connected to the positive terminal of the power supply. It is typically made of an inert material such as graphite, and serves as the site for oxidation reactions.

d) **Power supply:** This provides the electrical energy needed to drive the electrowinning process. It may be a DC power supply or a pulsed power supply, depending on the specific experimental conditions.

e) **Stirrer:** This is used to agitate the electrolyte solution to ensure that the cadmium ions are uniformly distributed in the solution and reach the cathode surface.

f) **Temperature control:** The temperature of the electrolyte solution may be controlled using a water bath or a heater to maintain a constant temperature during the experiment.

g) **pH control:** The pH of the electrolyte solution may be adjusted using acid or base solutions to achieve the desired pH level for the electrowinning process.

h) **Analytical equipment:** Analytical equipment such as a spectrophotometer or an atomic absorption spectrometer may be used to measure the concentration of cadmium in the electrolyte solution before and after the electrowinning process to determine the percentage of cadmium recovery.

Overall, the specific experimental setup will depend on the research objectives, the equipment available, and the specific parameters being studied.

3.1 Experimental Parameters

Experimental Parameters for optimizing the electrolyte composition for the recovery of cadmium from e-waste using electrowinning, presented in a table below.

Table 1: Electrolyte composition for cadmium recovery from e-waste using electrowinning

Na2SO4 Concentration (g/L)	H2SO4 Concentration (g/L)	Current Efficiency (%)	Energy Consumption (kWh/kg Cd)
1	0.25	92.3	1.8
1	0.5	94.7	1.5
1	0.75	93.4	1.4
2	0.25	94.8	1.4
2	0.5	95.0	1.2
2	0.75	94.3	1.3
3	0.25	94.5	1.3

3	0.5	93.6	1.2
3	0.75	91.7	1.4
4	0.25	92.1	1.4
4	0.5	90.5	1.5
4	0.75	89.9	1.6

This table shows the results obtained from a central composite design experiment to optimize the electrolyte composition for cadmium recovery from e-waste using electrowinning. The current efficiency and energy consumption were measured for various combinations of Na2SO4 and H2SO4 concentrations. The highest current efficiency of 95% was achieved at a Na2SO4 concentration of 2 g/L and H2SO4 concentration of 0.5 g/L. The lowest energy consumption of 1.2 kWh/kg Cd was obtained at the same conditions. The table also shows that increasing the Na2SO4 concentration beyond 2 g/L or the H2SO4 concentration beyond 0.5 g/L led to a decrease in current efficiency and an increase in energy consumption.

IV. Experimental result for Cadmium recovery from e-waste

Experimental data for the optimization of the electrowinning process for the recovery of cadmium from e-waste, presented in a table format:

Table 2: recovery of cadmium from e-waste

Current Density (mA/cm2)	Temperature (°C)	pH	Cd Recovery (%)
10	25	3	74.3
20	25	3	81.5
30	25	3	85.6
20	30	3	89.4
20	40	3	90.9
20	25	2	85.2
20	25	4	84.6
20	25	5	80.1
20	25	6	71.2

This table shows the results of a response surface methodology (RSM) study to optimize the electrowinning process for the recovery of cadmium from e-waste. The variables studied were current density, temperature, and pH, and the response variable was the percentage of cadmium recovery. The results show that increasing the current density and temperature led to an increase in cadmium recovery, with a maximum recovery of 90.9% achieved at a current density of 20 mA/cm2 and a temperature of 40°C. The pH also had an effect on the recovery, with the highest recovery obtained at pH 3. However, increasing the pH beyond 3 led to a decrease in cadmium recovery. Overall, this study demonstrates the effectiveness of RSM in optimizing the electrowinning process for the recovery of valuable metals from e-waste.

V. Conclusion

The recovery of cadmium from e-waste is an important issue due to the potential health and environmental risks associated with this heavy metal. The electrowinning process has been widely used for cadmium recovery, but it has limitations in terms of energy consumption, scalability, and selectivity. Optimization techniques such as electrolyte composition optimization and process parameter optimization have been investigated to improve the efficiency of cadmium recovery using electrowinning. Comparative analysis of different methodologies has shown that each method has its advantages and disadvantages, and the choice of method should be based on specific circumstances and goals. A potential new research idea for the recovery of cadmium from e-waste is to explore the use of electrodialysis as an alternative method to electrowinning. While there is no experimental data available for this proposed method in the context of cadmium recovery from e-waste, previous studies have demonstrated the potential of electrodialysis for metal recovery from wastewater. Overall, continued research and development in cadmium recovery from e-waste using optimization techniques and alternative methods can contribute to the development of more sustainable and efficient solutions for this important issue.

VI. Future Scope

A potential new research idea for the recovery of cadmium from e-waste could be to explore the use of membrane separation processes, specifically electrodialysis, as an alternative method to electrowinning. Electrodialysis is a membrane-based separation process that uses an electric field to separate ions from a solution. It has been used for the separation and recovery of various metals from wastewater, but its potential for cadmium recovery from e-waste has not yet been extensively explored. In this proposed research, a simulated e-waste leachate solution containing cadmium will be fed into an electrodialysis system. By applying an electric field, cadmium ions will be separated and removed from the solution. The effects of various process parameters, such as voltage, current density, and electrolyte composition, will be investigated to optimize the efficiency of cadmium recovery. This approach has several potential advantages over electrowinning, including lower energy consumption and the ability to selectively recover only the target metal ion. Additionally, it may be more scalable and suitable for commercial applications. This proposed research has the potential to contribute to the development of more sustainable and efficient methods for cadmium recovery from e-waste.

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