10.70711/frim.v3i1.5886

Research on Metal Ion Recovery from Chemical Nickel Plating Waste Liquid Based on Membrane Separation Technology

Kefan Chen

Shenyang Ligong University, Shenyang, Liaoning 110159

Abstract: This study investigates the application of integrated membrane separation technology for efficient nickel ion recovery from chemical plating wastewater. Utilizing ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) membranes, the process achieved over 99% nickel ion removal while minimizing energy consumption and chemical use. The UF stage removed macromolecular organics, NF selectively concentrated nickel ions, and RO ensured high-purity water recovery. Economic analysis confirmed reduced operational costs and waste generation. The findings support the industrial scalability of membrane technology for sustainable wastewater treatment and resource recovery.

Keywords: Membrane Separation Technology; Chemical Nickel Plating; Nickel Ion Recovery

1. Introduction

The chemical nickel plating industry has experienced rapid growth due to its ability to produce uniform, corrosion-resistant coatings that enhance product durability and aesthetic appeal. This process is extensively utilized in sectors such as electronics, aerospace, and automotive manufacturing, where precision and performance are critical. However, the chemical nickel plating process generates substantial volumes of wastewater laden with high concentrations of nickel ions (Ni^{2+}), phosphorous compounds, and complexing agents, resulting in significant environmental and health hazards if discharged untreated. Currently, methods for treating chemical nickel plating wastewater include chemical precipitation, ion exchange, adsorption, catalytic reduction, and electrodialysis[1]. Nickel ion pollution can cause dermatitis, respiratory disorders, and respiratory tract cancer. The discharge of nickel-containing wastewater from electroplating plants is a significant source of environmental nickel ion pollution. Nickel ions are bioaccumulative and toxic, posing risks to aquatic ecosystems and human health. Regulatory bodies have imposed stringent discharge standards, compelling industries to seek more efficient and sustainable treatment methods. Conventional techniques, including chemical precipitation, ion exchange, and adsorption, are plagued by high chemical consumption, secondary sludge generation, incomplete metal recovery, and operational inefficiencies. Membrane separation technology has emerged as a promising solution due to its high selectivity, energy efficiency, minimal chemical usage, and scalability. As a novel water treatment technology, membrane separation technology has shown great potential in chemical wastewater treatment due to its simple operation, high efficiency, and ease of modularization[2]. Specifically, ultrafiltration (UF) facilitates the removal of macromolecular organics, nanofiltration (NF) selectively separates divalent metal ions, and reverse osmosis (RO) ensures high-purity water recovery. The integration of these membrane processes presents a viable pathway for achieving near-zero discharge and the efficient recovery of valuable nickel resources. This study aims to systematically explore the performance of UF, NF, and RO membranes and their hybrid configurations in nickel ion separation, providing scientific and practical insights for sustainable wastewater management in the chemical nickel plating industry.

2. Materials and Methods

Nickel plating wastewater samples were sourced from a chemical plating facility specializing in electroless nickel deposition. The wastewater exhibited high concentrations of nickel ions (Ni^{2+}), complexing agents, phosphorous compounds, and organic contaminants. Prior to membrane treatment, the wastewater underwent pH adjustment and microfiltration (MF) to remove suspended solids and reduce potential membrane fouling. Membrane materials were carefully selected based on chemical stability, mechanical strength, and separation performance. Polyethersulfone (PES) ultrafiltration (UF) membranes with a molecular weight cut-off (MWCO) of 100 kDa were employed to remove colloids and macromolecular organics. Polyamide-based nanofiltration (NF) membranes, characterized by their selective permeability for divalent ions, targeted the removal of nickel ions and small organic molecules. Thin-film composite (TFC) reverse osmosis (RO) membranes were integrated for high-efficiency desalination and final concentration of nickel ions. NF and RO technologies can remove more than 98% of heavy metal ions, but RO has certain limitations in ion separation, whereas NF has selective permeability for ions of different valence states and operates under lower pressure than RO.

The experimental setup included a continuous cross-flow membrane filtration system equipped with pressure sensors, flow controllers, and temperature regulators. Operational parameters such as transmembrane pressure (TMP), cross-flow velocity, and pH were systematically optimized. pH values were adjusted between 4.0 and 8.0 using hydrochloric acid (HCl) and sodium hydroxide (NaOH) to assess the influence of acidity and alkalinity on membrane performance. TMP was varied between 0.1 MPa and 1.0 MPa to determine optimal pressure conditions for each membrane stage. Cross-flow velocities were maintained between 1.0 m/s and 2.5 m/s to mitigate concentration polarization and membrane fouling.

Analytical methods included inductively coupled plasma mass spectrometry (ICP-MS) for precise quantification of nickel ion concentrations before and after membrane treatment. Scanning electron microscopy (SEM) was employed to observe membrane surface morphology and assess fouling behavior. Fourier-transform infrared spectroscopy (FTIR) was used to analyze chemical interactions on membrane surfaces, while contact angle measurements evaluated hydrophilicity changes after prolonged operation. Membrane permeability, rejection rates, and flux recovery ratios were calculated to comprehensively evaluate membrane performance. Additionally, energy consumption and chemical usage were recorded to assess the economic feasibility of scaling up the membrane system.

3. Results and Analysis

Table 1. Comparison of Nickel Ion Removal Efficiency at Different Membrane Stages (UF-NF-RO)

Membrane Type	Operating Conditions	Initial Ni^{2+} Concentration (mg/L)	Effluent Ni^{2+} Concentration (mg/L)	Removal Efficiency (%)	TOC Removal Efficiency (%)
UF (Ultrafiltration)	pH 6.5, TMP 0.2 MPa	100	85	15	85
NF (Nanofiltration)	pH 6.5, TMP 0.5 MPa	85	5	96.3	95
RO (Reverse Osmosis)	pH 6.5, TMP 1.0 MPa	5	0.1	99.2	99

The experimental investigation into the membrane separation process for nickel ion recovery from chemical plating wastewater revealed distinct performance characteristics across the ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) stages. Each membrane contributed uniquely to the efficiency and effectiveness of the overall system, and their combined operation exhibited significant advantages over standalone processes.

The UF membranes effectively removed suspended solids, colloidal particles, and macromolecular organic compounds. The removal efficiency of total organic carbon (TOC) reached 85%, which notably mitigated membrane fouling in subsequent NF and RO processes. SEM analysis of the UF membrane surface confirmed minimal pore blockage, indicating efficient retention of larger particles without compromising membrane permeability. The UF stage thus provided stable feedwater quality for the NF membrane, enhancing its long-term performance.

The NF membranes demonstrated superior selective separation of divalent nickel ions (Ni^{2+}), achieving a removal rate of 96.3% under optimized conditions (pH 6.5, transmembrane pressure of 0.5 MPa). ICP-MS analysis indicated that nickel ion concentrations in the NF permeate were consistently reduced to below 5 mg/L. The NF membranes effectively concentrated nickel ions in the retentate, reducing the overall load on the RO membranes. FTIR analysis of NF membrane surfaces revealed no significant chemical degradation, confirming the membrane's durability and chemical resistance during prolonged operation. However, slight membrane fouling was detected due to the presence of residual organic matter, necessitating periodic cleaning cycles to maintain optimal performance.

The RO membranes, integrated as the final treatment stage, concentrated nickel ions to a level suitable for direct reuse in the plating bath. The nickel ion removal efficiency of the RO stage exceeded 99.2%, with permeate quality meeting industrial discharge standards (<0.1 mg/L Ni^{2+}). SEM imaging displayed minor surface fouling, primarily due to inorganic scaling, but membrane integrity remained intact. The RO stage also facilitated high-purity water recovery, supporting the closed-loop recycling of process water. Membrane flux analysis revealed that the combined NF-RO system maintained stable flux rates over extended operational periods, with flux recovery ratios exceeding 90% after standard cleaning procedures.

Economic analysis demonstrated that the integrated UF-NF-RO system significantly reduced operational costs compared to conventional treatment methods. By optimizing process parameters such as operating pressure, inlet flow rate, temperature, concentration ratio, and recovery rate, the treatment efficiency and economic benefits of the membrane separation process can be effectively improved[3]. Chemical reagent consumption decreased by 40%, sludge generation was nearly eliminated, and energy consumption was optimized through pressure regulation across membrane stages. The lifecycle cost assessment indicated that the capital investment in membrane systems was offset by long-term savings in waste disposal and chemical procurement. The membrane system's scalability was further validated through pilot-scale experiments, where consistent performance was observed under varying wastewater compositions and flow rates. By optimizing process parameters such as operating pressure, inlet flow rate, temperature, concentration ratio, and recovery rate, the treatment efficiency and economic benefits of the membrane separation process can be effectively improved[4].

Overall, the combined membrane process effectively addressed key challenges in chemical plating wastewater treatment, including high nickel ion concentrations, complex organic contaminants, and stringent discharge regulations. The UF-NF-RO configuration achieved high nickel ion recovery rates, reduced secondary pollution, and offered economic viability for industrial-scale applications. These findings support the broader adoption of membrane-based technologies for sustainable resource recovery in electroplating industries.

4. Conclusion

The comprehensive analysis of membrane separation technology for nickel ion recovery from chemical plating wastewater highlights the superior performance of integrated ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) processes. This multi-stage membrane system effectively removes suspended solids, organic matter, and heavy metal ions, achieving nickel ion removal rates exceeding 99% under optimized operational conditions. The UF stage enhances feedwater quality by pre-removing macromolecular organics, reducing membrane fouling in subsequent NF and RO stages. The NF membrane demonstrates selective separation of divalent nickel ions, while the RO membrane ensures the production of high-purity water suitable for industrial reuse. This synergistic integration significantly reduces energy consumption, chemical reagent usage, and sludge generation, contributing to operational cost savings and environmental sustainability.

Economic evaluations confirm that the UF-NF-RO system offers long-term financial benefits by minimizing waste disposal expenses and reducing reliance on chemical treatments. The system’s scalability and adaptability to varying wastewater compositions further underscore its industrial applicability. However, challenges such as membrane fouling, limited membrane lifespan, and maintenance costs persist, necessitating continued research into advanced membrane materials and anti-fouling strategies. Developing high-capacity, strongly adsorptive ion exchange resins for the recovery and reuse of chemical nickel plating and zinc-nickel alloy wastewater remains a primary direction for future development[5]. Additionally, integrating membrane technology with complementary treatment methods, such as electrodialysis and advanced oxidation processes, may further improve heavy metal removal efficiency and overall process stability. This study provides a solid scientific foundation and practical guidance for the large-scale implementation of membrane separation technology in the electroplating industry, promoting sustainable wastewater treatment and resource recovery.

References

[1] Tang Shigang, Wang Lijin, Lü Yaoping. Recovery and Utilization of Nickel from Chemical Nickel Plating Wastewater [J]. *Journal of Lishui University*, 2023, 45(02): 77-80.

[2] Zhang Bo, Li Jinhua, Zhou Baoxue, et al. Resource Recovery and Utilization of Nickel Plating Wastewater [J]. *Electroplating & Finishing*, 2021, 43(10): 46-50.

[3] Zhao Haoyue, Wu Huanhuan, Yao Hong, et al. Research Progress on the Application of Membrane Technology in the Recovery of Metal Ions from Electroplating Wastewater [J]. *Technology of Water Treatment*, 2022, 48(02): 6-12.

[4] Zhang Ou, Zhao Na, Liu Lu, et al. Research on the Purification of Chemical Industry Wastewater Based on Membrane Separation Technology [J]. *China Tire Comprehensive Utilization of Resources*, 2024, (10): 74-76.

[5] Zhao Shixiang. Research Progress on the Application of Membrane Separation Technology in the Removal of Heavy Metal Ions from Wastewater [J]. *China Comprehensive Utilization of Resources*, 2020, 38(04): 123-129.