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A Comparative Review of Removing Chromium (VI) from Electroplating Industry Wastewater Using Electrocoagulation and Membrane Filtration

Bingjie Li[1, *], Yue Wang[2]

[1]Faculty of Arts and Science, University of Toronto, Toronto, M5S 1A1, Canada, selenabingjie.li@mail.utoronto.ca

[2]Ulink High School of Suzhou Industrial Park, Suzhou, China, 215000, China, yue.wang2006@gmail.com

*Corresponding author email: selenabingjie.li@mail.utoronto.ca

Abstract:

This comparative review aims to evaluate the effectiveness, efficiency, and feasibility of two treatment methods—Electrocoagulation (EC) and Membrane Filtration (MF)—for removing hexavalent chromium (Cr (VI)) from electroplating industry wastewater. Cr (VI) is a highly toxic and carcinogenic contaminant, necessitating efficient removal techniques. This study reviews recent literature on EC and MF's operational principles, performance metrics, and environmental impacts. Key findings indicate that while EC offers precise treatment with lower initial costs, MF provides higher removal efficiency and can handle larger wastewater volumes. Both methods exhibit specific advantages and limitations regarding operational costs, maintenance, and environmental impact. The review concludes that the treatment method choice should be based on specific situational requirements, emphasizing the need for further research to optimize these technologies.

Keywords: Electrocoagulation, Membrane Filtration, Electroplating Industry Wastewater

1. Introduction

Chromium is a heavy metal with high solubility and persistence in the environment (Ahmed & Mokhtar, 2020). Chromium is considered one of the most critical and pressing environmental concerns among common heavy metals due to its high solubility and chemical stability. This is illustrated in the table 1.

Table 1. Characteristics of Common Heavy Metals in Wastewater, Including Bulk and Leachate Concentrations and Chemical Resistance

Heavy Metal	Typical Bulk Concentration (mg/L)	Typical Leachate Concentration (mg/L)	Resistance
Chromium (Cr)	0.1 - 0.5	0.01 - 0.5	High (inorganic forms are resistant to chemical oxidation and reduction, but hexavalent chromium is more reactive)
Manganese (Mn)	0.05 - 3.0	0.01 - 0.3	Moderate (oxidation state changes can occur, affecting solubility and mobility)
Nickel (Ni)	0.01 - 2.0	0.05 - 0.2	Moderate to High (depends on pH and complexing agents; generally resistant under neutral to alkaline conditions)
Copper (Cu)	0.05 - 1.5	0.02 - 1.0	Moderate (forms stable complexes with organic matter, resistant under alkaline conditions)
Lead (Pb)	0.005 - 0.5	0.001 - 0.05	High (forms stable precipitates with sulfates and carbonates, highly resistant in reducing conditions)
Iron (Fe)	0.1 - 10.0	0.01 - 1.0	Low to Moderate (readily oxidizes and reduces; iron oxides and hydroxides are common in aerobic conditions)
Zinc (Zn)	0.01 - 5.0	0.005 - 0.5	Moderate (susceptible to precipitation at high pH; forms stable complexes with organics)

The hexavalent form of chromium, Cr(VI), is particularly toxic and carcinogenic, posing severe health risks such as respiratory issues, skin irritation, and lung cancer (Lazarova et al., 2014). Cr(VI) is also detrimental to aquatic life, causing mutations and fatalities. Electroplating processes, which use valuable metals like chromium, nickel, and copper, are significant sources of chromium pollution. What's more, the distribution of Cr in the aquatic system around the world became serious after the 2000s, as shown in Figure 1 and Figure 2.

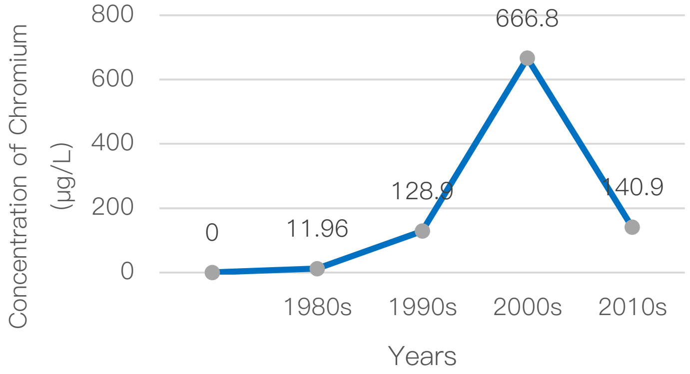

Figure 1. Total Chromium Levels (μg/L) and Corresponding Sample Numbers (SN) for Global River and Lake Water Between the 1980s and the 2010s

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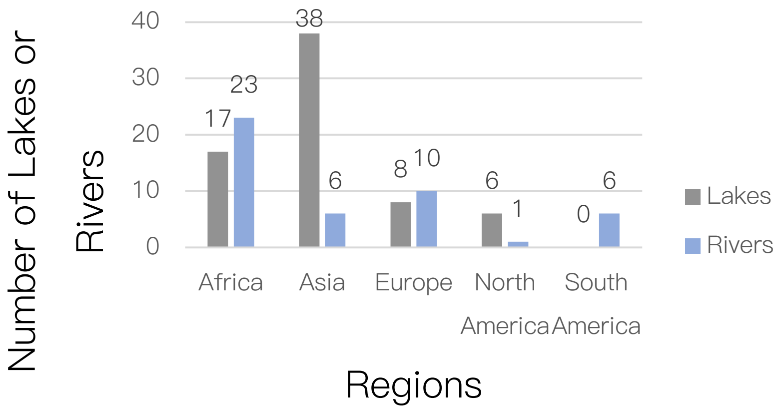

Figure 2. Quantity and Geographical Distribution of the Rivers and Lakes Reviewed

The urgency of removing chromium from electroplating wastewater is underscored by its proximity to human populations and ecosystems.

Traditional methods such as chemical precipitation, ion exchange, adsorption, and reduction have been employed to treat electroplating wastewater. However, these methods often face high costs, secondary pollution, and the need for large quantities of chemicals (Peng & Guo, 2020). Moreover, they may not achieve the desired removal efficiency, especially with complex wastewater matrices or low Cr (VI) concentrations.

This review compares two commonly used technologies for removing Cr (VI) from electroplating wastewater: Membrane Filtration (MF) and Electrocoagulation (EC). Membrane Filtration uses semi-permeable membranes to separate contaminants based on size or charge (Anarakdim et al., 2020; Zhao et al., 2019). Electrocoagulation is an electrochemical process that uses electric current to dissolve sacrificial anodes into the wastewater. The resulting metal ions react with contaminants, forming insoluble compounds easily separated from the water (Peng & Guo, 2020).

This comparative review aims to evaluate EC and MF's performance, efficiency, and feasibility in removing Cr (VI) from electroplating wastewater. Addressing this issue is hoped to contribute to developing more effective and sustainable treatment strategies, ensuring that polluted areas can thrive once more, free from the shadow of pollution. Treating wastewater also allows for the recovery and reuse of valuable metals, reducing the need for raw material extraction and lowering operational costs (Huang et al., 2013). Additionally, treating electroplating wastewater demonstrates industries' responsible attitude towards society and enhances their reputation.

2. Method

The research was conducted by limiting the range of published years and using specific keywords to find appropriate studies. The reviews and studies searched were mainly from the last 3-5 years, with some background knowledge from older studies. The keywords used included Membrane, Nanofiltration, Reverse Osmosis, Electrocoagulation, Electrochemical, Electroplating Wastewater, and Chromium. The research was conducted separately for the two treatments, and the information was collected and compared.

2.1 Membrane Filtration

Due to their simple separation methods, membrane processes are employed in treating water and wastewater (Anarakdim et al., 2020; Zhao et al., 2019). Membrane filtration uses a semi-permeable membrane to separate contaminants from water based on their size, charge, and chemical properties. The process involves the application of pressure to drive water through the membrane while retaining contaminants, including chromium ions, on the membrane surface or within its structure. This process is divided into membrane types with minor differences (Peng & Guo, 2020).

Table 2 shows five types of membrane processes used in water and wastewater treatment: electrodialysis, microfiltration, ultrafiltration, nanofiltration, and reverse osmosis (Cheremisinoff, 2002). Currently, Nanofiltration (NF) and Reverse Osmosis (RO) are primarily used to treat Cr(VI) in polluted water (Wang et al., 2022).

Table 2. Comparison of Membrane Filtration Techniques in Electroplating Wastewater Treatment

Filtration Technique	Typical Applications in Electroplating Wastewater	Pore Size (nm)	Effective Particle/ Molecule Size Removed	Usage in Treating Electroplating Wastewater	Advantages	Disadvantages
Microfiltration (MF)	Removal of suspended solids, bacteria, and large colloids	100 - 1000	> 100 nm	Less Common	Simple operation, low energy consumption	Not effective for dissolved ions or metals
Ultrafiltration (UF)	Removal of macromolecules, proteins, and fine colloids	2 - 100	1 - 100 nm	Less Common	Can remove larger molecules and some colloidal metals	Ineffective for small dissolved ions and heavy metals
Nanofiltration (NF)	Removal of divalent ions, organic molecules, and some heavy metals (e.g., Ni, Cu)	1 - 2	0.5 - 2 nm	More Common	Effective for partial desalination and metal removal	Requires higher pressure than MF and UF, moderate fouling
Reverse Osmosis (RO)	Removal of almost all dissolved ions, heavy metals, and small organics	< 1	< 0.5 nm	Most Common	High efficiency in removing ions, heavy metals, and organics	High energy consumption, high-pressure requirements, fouling
Electrodialysis (ED)	Selective removal of ions based on charge	N/A (Ion exchange membranes)	Ionic scale	Occasionally Used	Effective for ionic separation and concentration	High energy costs for high ionic strength solutions

Based on membrane filtration principles, this process's characteristics are evaluated from three perspectives: Efficiency, Cost, and Environmental Impact. Membrane filtration allows for selective filtration, achieving high removal rates of Cr(VI) between 90-99% and reducing concentrations below regulatory limits (Al-Alawy & Salih, 2017). Some studies show a 100% Cr(VI) reduction within 60 minutes under suitable conditions (He et al., 2022). Membrane systems can handle large volumes of wastewater (Park et al., 2022; Muthumareeswaran et al., 2017) and are suitable for continuous inflow treatment (Shim et al., 2018). The required conditions for membranes are not harsh, with optimal performance typically around 23-35 degrees Celsius (Ye et al., 2019). Membrane systems are effective across various pH levels, typically between pH 3-7, for NF membranes to remove Cr(VI) (Wei et al., 2019). However, membranes can foul, especially in the presence of substances like divalent lead (Pb2+), which can reduce filtration efficiency and lead to costs for cleaning or replacing membranes (Wang et al., 2019).

Membrane filtration requires little energy and no chemicals, making it cost-effective (Park et al., 2022). Recent findings suggest that recovering metals like chromium during membrane filtration is feasible, reducing raw material costs (Engstler et al., 2022). However, the initial investment costs and the need for periodic replacement can be financial barriers for small industries (Pezeshki et al., 2023).

The membrane filtration process uses environmentally friendly raw materials. A recent study shows the possibility of making PET membranes from reusable water bottles (Ali et al., 2023). However, the process generates reverse osmosis concentrate (ROC), which requires further treatment, such as forward osmosis (Kazner et al., 2014).

2.2 Electrocoagulation

Electrocoagulation (EC) is a water treatment process that uses the direct conduction of electric current within electrodes (cathode and anode) immersed in wastewater, which serves as an electrolyte. When electrical energy is applied to the anode, aluminum or iron is introduced into the solution, which reacts with hydroxide ions (OH^-) produced at the cathode, forming aluminum hydroxide. (Hartati et al., 2024) This compound initiates coagulation processes, effectively eliminating suspended particles from the wastewater. Key parameters influencing the efficacy of electrocoagulation include voltage, duration, wastewater pH, and the conductivity of the electrocoagulation reactor and electrodes (Xu et al., 2019). The reactions occurring within an electrochemical cell, where the metal (M) acts

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as the sacrificial electrode, include:
at the cathode:
$2\ H_2O(l) + 2\ e^- \rightarrow 2\ H_2(g) + 2\ OH^-$
at the anode:
$M(s) \rightarrow Mn+ (aq) + n\ e^-$
$2\ H_2O(l) \rightarrow 4\ H+ (aq) + O_2(g) + 4e^-$
Specific reactions include:
$HCrO_4^- + 7H^+ + 3e^- \rightarrow Cr^{3+} + H_2O$
$CrO_4^{2-} + 4\ H_2O + 3e^- \rightarrow Cr(OH)^3(s) + 5OH^-$
Operating cost is a crucial parameter in evaluating the viability of any treatment method. The primary components of operating expenses for lab-scale electrocoagulation units are energy and electrode material costs. These can be estimated using the following equation:
Operating Cost = An Energy Consumption + B Electrode Consumption
Where A and B represent the prices of electrical energy and electrode material, respectively.

3.Results

The comparison of Membrane Filtration (MF) and Electrocoagulation (EC) was conducted across four critical aspects: efficiency, loss, cost, and environmental impact. Membrane filtration passes water through a selective barrier, which removes contaminants based on size and other properties. Electrocoagulation uses electrical currents to destabilize and remove impurities. EC performs better in selective removal, requiring fewer specific conditions to achieve high removal rates. (Deghles and Kurt, 2017) However, MF is particularly effective in treating large volumes of water with easily achievable condition requirements, making it a more efficient solution. EC offers more precise treatment, while MF can save more time removing chromium (Wu, 2021).
Both MF and EC incur some losses. Membranes can lose part of their functionality over time as they become saturated with contaminants (Lu et al., 2021) and require periodic replacement. EC electrodes, once fully utilized, also lose effectiveness as they sacrifice the electrode. However, a significant advantage of EC is that after fouling, the electrodes can be treated and reused by reversing the polarity, thus extending their lifespan (Fuladpanjeh-Hojaghan et al., 2020). This reusability feature helps in decreasing the loss associated with the EC process.
Cost considerations for both methods vary. MF systems often have higher initial construction costs (Judd & Carra, 2021) and require regular membrane replacement and maintenance. Although EC may incur operational costs such as energy consumption and electrode consumption (Etih Hartati et al., 2024), it is generally simpler and more cost-effective to establish and maintain. (Patel et al., 2022) Both methods have the advantage of enabling the recycling of resources, leading to long-term economic benefits. Therefore, while MF may have higher upfront costs, EC offers a more budget-friendly approach with easier maintenance.
Both methods produce waste that requires secondary treatment, posing additional environmental challenges. EC generates by-products that tend to produce more secondary waste. MF might offer a greener alternative by reducing secondary waste produced during treatment. Therefore, MF can be seen as a more sustainable option.

4.Discussion

When comparing Membrane Filtration and Electrocoagulation, several limitations need to be acknowledged. Most data for this comparison are derived from individual studies focusing on each method separately. There is a notable absence of direct comparative experiments, which limits the reliability of conclusions drawn from indirect comparisons. The analysis of Membrane Filtration has primarily focused on traditional methods, excluding many emerging technologies and advanced techniques. The recovery of heavy metals from the MF process is not mature and still requires a long time to develop. Further innovation and creation in this area are still required.
The choice between MF and EC should be based on specific situational requirements and conditions. This analysis has taken a more general approach, but in practice, a detailed site-specific evaluation is necessary to determine the most suitable method. This analysis has not explored the potential benefits of combining MF and EC. Hybrid approaches might overcome the limitations of each individual method and lead to improved overall efficiency and effectiveness. These limitations highlight the need for more comprehensive studies and site-specific assessments to determine the optimal method for a given application accurately.

5.Conclusion

This comparative review evaluated the performance, efficiency, and feasibility of Electrocoagulation (EC) and Membrane Filtration (MF) in removing hexavalent chromium (Cr(VI)) from electroplating industry wastewater. The findings indicate that EC offers precise treatment with lower initial costs and the potential for electrode reusability, making it a cost-effective option. Conversely, MF provides higher removal efficiency, can handle larger volumes of wastewater, and is environmentally friendly, albeit with higher initial investment and maintenance costs. Both methods have their specific advantages and limitations. Therefore, the treatment method choice should be based on the specific requirements of the wastewater treatment scenario, considering factors such as cost, efficiency, operational conditions, and environmental impact.

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