Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268
(Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 23 No. 2 pp. 649-665 2024

Review Research Paper
https://doi.org/10.46488/NEPT.2024.v23i02.005
Open Access Journal

Application of Membrane Separation Technology in Electroplating Wastewater Treatment and Resource Recovery: A Review

Le Zhang*† , Ying Chen , Huan Zhang***, Yabin Jin*, Zhe Shen* and Gending Duan***
*The Institute of Energy and Architecture, Xi'an Aeronautical Institute, Xi'an 710077, PR of China
**Shaanxi LvYuan Testing Technology Co. Ltd., Xi'an 710116, PR of China
***College of Chemistry and Material, Weinan Normal University, Weinan 714099, PR China
†Corresponding author: Le Zhang; zl_202106011@163.com

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 09-10-2023
Revised: 16-11-2023
Accepted: 17-11-2023

Key Words:
Electroplating wastewater
Heavy metals
Treatment
Membrane technology
Hybrid process

ABSTRACT

The rapid development of industry has led to the generation of a large amount of electroplating wastewater. The direct discharge of untreated electroplating wastewater may lead to the formation of toxic metal-organic complexes, which is a challenging problem for human health and the living environment of organisms. Due to the high solubility of heavy metals in aquatic environments and their easy absorption by organisms, effective treatment of electroplating wastewater is of great significance. The ultimate goal of electroplating wastewater treatment should be to recover metals and water from electroplating wastewater. In indoor experiments, pilot tests, and industrial applications of electroplating wastewater treatment, membrane treatment technology commonly used in wastewater terminal treatment has attracted great attention. Membrane treatment technology seems to be the most promising method for removing heavy metals and organic pollutants from electroplating wastewater. This article reviews the membrane treatment technologies for electroplating wastewater, introduces the advantages and disadvantages of various membranes in the treatment of electroplating wastewater, the removal efficiency of pollutant types, and their comparison. The focus is on the treatment effects of nano-filtration membrane, ultra-filtration membrane, micro-filtration membrane, reverse osmosis membrane, ceramic membrane, biofilm, etc., on electroplating wastewater. Compared with a single treatment method, the combination of different processes shows higher efficiency in removing various pollutants.

INTRODUCTION

With the rapid development of society and the economy and the continuous improvement of urbanization, water pollution has become increasingly severe, and water resources are in serious shortage (Guven et al. 2022). Strengthening sewage treatment and protecting water resources to achieve sustainable development is an essential and urgent task (Maulin et al. 2022). In recent years, the increasingly mature membrane separation technology has been widely used in industrial wastewater and domestic sewage purification, applied water treatment, seawater desalination, brackish water desalination, and other water treatment fields. This is due to its numerous advantages, such as excellent separation effects, energy-saving, and environmentally friendly nature, a simple process, convenient operation, and a small footprint (Sm et al. 2022, Ahmed et al. 2022).

Membrane separation technology uses a selectively permeable membrane made of special organic or inorganic materials, driven by external energy or a chemical potential difference, to separate, grade, purify, and concentrate mixtures (Ibrar et al. 2022). As membrane separation technology develops, new membrane materials have become a focal point and area of significant research interest (Manetti & Tomei 2022). The research and development of new membrane materials mainly include nano-fiber membrane-supported polymer composite membranes, organic-inorganic hybrid membranes, and inorganic membranes (Rodenburg et al. 2022). Membrane separation technology can be categorized according to pore size and filtration accuracy into the following types: micro-filtration (MF), ultra-filtration (UF), nano-filtration (NF), reverse osmosis (RO), and electrodialysis (ED) (Malhas et al. 2022).

The research demonstrated that a PET nanofiber membrane was prepared using electrostatic spinning. This PET nanofiber membrane was then used as a substrate and coated with crosslinked chitosan (Mansor et al. 2021). Subsequently, interfacial polymerization of m-phenylenediamine (MPD) and trimethylene chloride (TMC) was carried out to create a nanofibril polyamide composite reverse osmosis membrane (Khan & Boddu 2021). The membrane's rejection rate for a 2 g.L^{-1} sodium chloride solution reached 92%, with a corresponding flux of 21g/(m^2.h), showcasing good interception performance that can satisfy the requirements for high-purity water. Other studies have indicated that chemical bonding between organic and inorganic materials can be achieved through molecular design and surface modification of organosilicon materials and inorganic nanomaterials. This results in the pervaporation of organic compounds with excellent flux, selectivity, solvent resistance, and stability. At 50°C, the flux of a 5% ethanol aqueous solution is greater than 1000 g/(m^2.h), and at 70°C, the separation factor for a 1% butanol solution exceeds 70, with a flux of more than 1300 g/(m^2.h) (Ahin 2021).

In recent years, besides focusing on membrane materials research, some experts and scholars have made progress in studying membrane wastewater treatment technology. It has been reported that a biofilm reactor is created by combining biological treatment and membrane separation technology (Salgot & Folch 2018, Biniaz et al. 2019). With pore sizes ranging from 0.03 to 0.2 µm, the membrane exhibits a high-efficiency interception and separation effect. As microorganisms are entirely retained within the reactor, pollutants can be efficiently degraded and separated, resulting in high-quality water (Biniaz et al. 2019).

The micro-filtration combined technologies of coagulation-micro-filtration, adsorption-micro-filtration, and precipitation-micro-filtration can effectively play the advantages of dissolved salts, adsorbents, precipitators, and micro-filtration membranes, strengthen the separation effect and effectively reduce membrane pollution (Rahimpour et al. 2019). The research shows that the integrated technology of membrane filtration and adsorption can control the flow rate and time of stock solution entering the membrane module, adjust the solute concentration of the concentration difference polarization layer, and extract and derive the concentrated solution of the concentration difference polarization layer in time, and solve the two significant problems of concentration difference polarization and membrane pollution at the same time (Damtie et al. 2018, Leonzio 2017)

At present, membrane treatment technology is widely used in sewage treatment. Despite the many research achievements in electroplating wastewater treatment, there are fewer instances of membrane treatment technology implemented in industrial applications (Cho et al. 2018). Electroplating wastewater is characterized by an overly complex composition, increasing discharge year by year, and progressively high pollutant concentrations, posing a significant challenge to adequate environmental protection (Silva et al. 2017). Chemical precipitation technology is commonly used for treating electroplating wastewater (Fig. 1) (Ozokwelu et al. 2017). However, due to the addition of numerous chemicals during the treatment process, the treated wastewater's salinity increases significantly, severely affecting the biodegradability of wastewater in the later stages of the process. At the same time, many

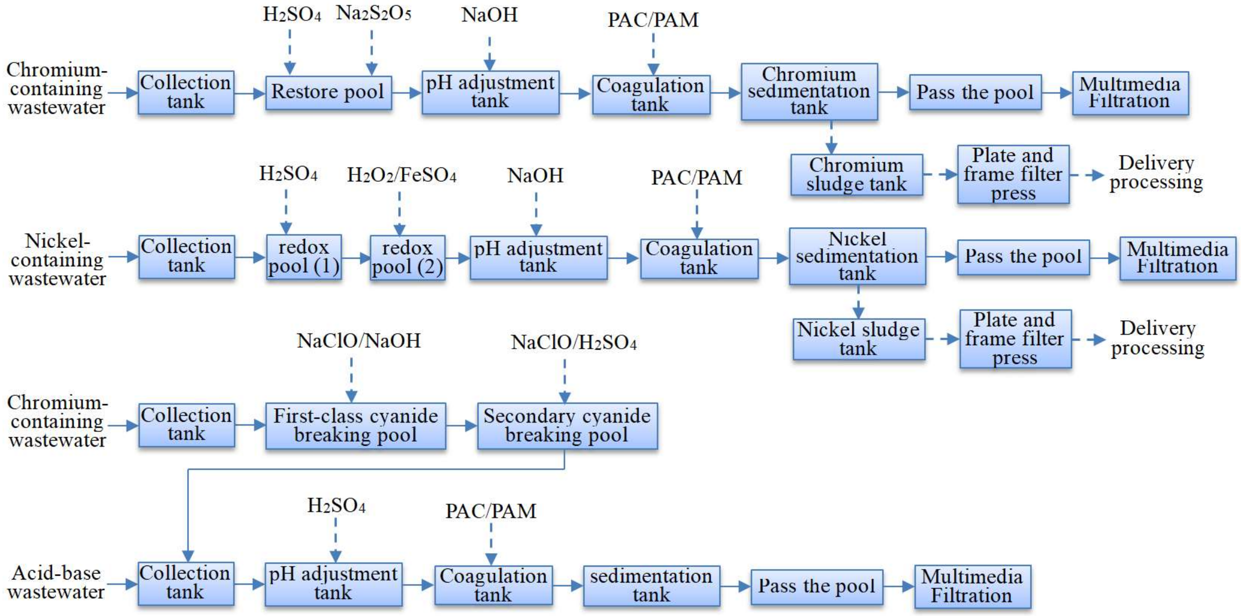


Fig. 1: Several common electroplating wastewater chemical treatment processes.

heavy metals are lost from the wastewater, and substances such as ammonia, nitrogen, and total phosphorus become challenging to remove in subsequent processes (Hosseini et al. 2017). Moreover, the treatment process generates a considerable amount of sludge, which results in a low reuse rate of reclaimed water and significantly increased reuse costs (Noah et al. 2016, Babilas & Dydo 2018). The latest "Emission Standard of Electroplating Pollutants" (GB21900-2008), implemented in our country in 2008, sets higher requirements for the discharge concentration limits of heavy metals and other related indicators in electroplating wastewater. Therefore, adopting more environmentally friendly production processes and advanced wastewater treatment technologies that meet these requirements is essential for solving the problem of up-to-standard discharge of electroplating wastewater (Hoslett et al. 2018).

Due to its excellent treatment effects and robust adaptability, membrane treatment technology has emerged as an advanced method for the harmless and efficient treatment of electroplating wastewater (Al-Saydeh et al. 2017, Akar et al. 2021). The typical membrane filtration process is illustrated in Fig. 2, where large particle contaminants accumulate on the surface while smaller particles either pass through the membrane pores or remain within them. Applying membrane treatment technology for electroplating wastewater results in a wastewater reduction treatment process (Sur & Mukhopadhyay 2018, Wen et al. 2018). In this process, the amount of chemicals added is minimal. Following pretreatment of the wastewater, it directly enters the membrane element for concentration. The final effluent meets the requirements for reuse, and the concentrated wastewater can be recycled. Consequently, the volume of wastewater requiring discharge is significantly reduced, along with sludge production, leading to decreased treatment costs (Wen et al. 2018).

A large number of practices using membrane separation technology to treat industrial electroplating wastewater have shown that different membrane properties have different requirements for the ability to separate water quality and treatment. For example, composite membranes, porous membranes, and exchange membranes are mainly treated with non-organic ions, bacteria, and inorganic ions. Electroplating wastewater is rich in a large amount of heavy metals and contains many anions that are harmful to human health. At the same time, the acidity and alkalinity of the wastewater are also different from normal water quality. Therefore, solving some impurities in the wastewater and reusing industrial wastewater to obtain useful substances cannot be done without the use of membrane separation technology.

This article aims to summarize the application research of membrane treatment technology for electroplating wastewater and theoretically analyze the treatment effects and development prospects of nano-filtration membrane, ultra-filtration membrane, micro-filtration membrane, reverse osmosis membrane, ceramic membrane, biofilm, etc., on electroplating wastewater. At the same time, it considers the technical defects and potential problems that membrane treatment technology may face in the electroplating wastewater treatment process.

CHARACTERISTICS AND HAZARDS OF ELECTROPLATING WASTEWATER

Characteristics

Sources of electroplating wastewater: waste electroplating solution, washing wastewater during equipment maintenance, wastewater from washing workshops, cleaning water for electroplating parts, condensed water formed by condensation of ventilation equipment, seepage or leaking water from aqueducts, and various bath liquids during improper operation and drained wastewater (Akar et al. 2021).

Due to the different requirements of each plating piece, the relevant technical conditions, such as the electroplating

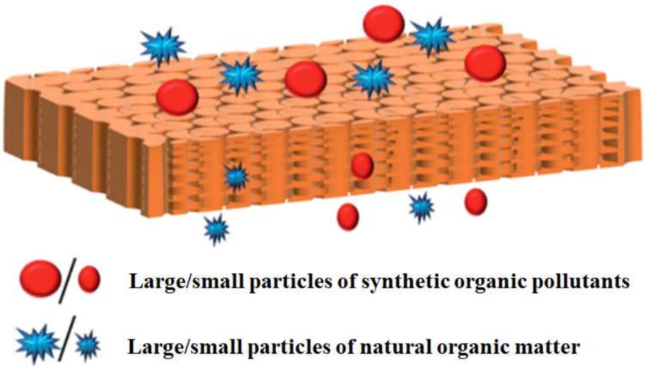


Fig. 2: The usual membrane filtration process.

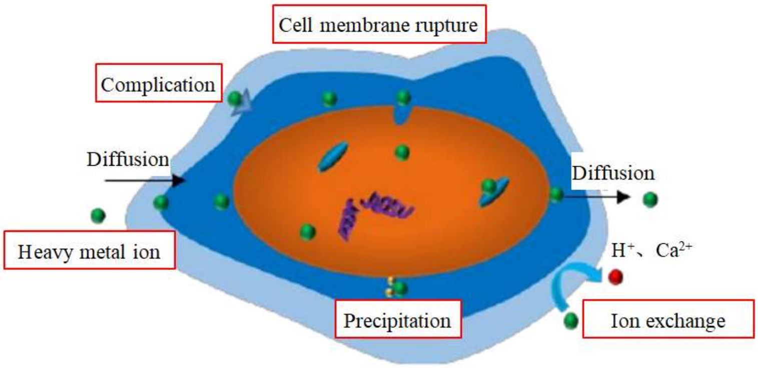


Fig. 3: Toxicity mechanism of heavy metal ions on cells.

solution and coating layer selected during electroplating, are also different, so the formed electroplating wastewater contains a wide variety of pollutants and significant differences between components (Albergamo et al. 2019). In addition to many heavy metal ions, wastewater contains various citric acids, surfactants, cyanide, etc (Akar et al. 2021, Albergamo et al. 2019).

Hazards

The electroplating industry will produce a large amount of electroplating wastewater in production. Such wastewater contains heavy metal ions such as chromium, copper, nickel, cadmium, zinc, and more toxic compounds such as cyanide (Mohagheghian et al. 2018). Once these toxic and refractory substances enter the natural environment, they will exist in nature for a long time. They can eventually be enriched in animals and plants through the food chain in the ecological cycle and even eventually in the human body at the top of the food chain. It can destroy the cells and tissues of the human body (Fig. 3) (Takuma et al. 2018). Symptoms such as poisoning, cancer, aberration, and mutation that lead human body will bring great harm and impact human beings and the social environment (Mohagheghian et al. 2018).

Therefore, before treating electroplating wastewater, the source, type, and pollution degree of pollutants in the wastewater should be identified first to be recovered and treated safely and effectively. All electroplating wastewater can be recovered by strictly controlling the discharge content of pollutants. Discharge up to the standard to protect the environment so that wastewater pollution will not cause harm to society and human health (Sur & Mukhopadhyay 2018, Abdel & Alseroury 2019).

CURRENT SITUATION AND PROBLEMS OF TREATMENT OF ELECTROPLATING WASTEWATER

The treatment process of electroplating wastewater mainly includes four parts: pretreatment, comprehensive treatment, membrane treatment, and evaporation treatment (Kobya et al. 2017). The pretreatment stage of wastewater generally follows the principles of classified collection and qualitative treatment. For example, the pretreatment of wastewater containing cyanide adopts the alkaline chlorination method, the pretreatment of wastewater containing chromium adopts the sulfite reduction method, and the pretreatment of wastewater containing nickel, cadmium, and copper. The pretreatment of wastewater, such as zinc, adopts the chemical precipitation or ion exchange method, and the pretreatment of acid-base wastewater adopts the neutralization method (Castel & Favre 2018, Hackbarth et al. 2016). After pretreatment, all kinds of wastewater will enter the comprehensive treatment stage. In the comprehensive treatment stage, technologies such as physicochemical and biochemical treatment are used to remove different pollutants, such as organic matter, ammonia nitrogen, and total nitrogen, so that the effluent meets the influent requirements of membrane treatment. In the membrane treatment section, the multi-stage and multi-stage combined membrane process concentrates and reduces the amount of wastewater (Hedayati et al. 2017). The high salinity membrane system produces water and evaporative condensate water, which is recycled back to production to achieve zero discharge of electroplating wastewater (John et al. 2016).

Due to the complex composition of electroplating wastewater, difficult control of composition, significant variation in water quality, and intense pollution, the current treatment of electroplating wastewater has the following problems (Hackbarth et al. 2016).

Unreasonable Classification

Although electroplating wastewater generally follows the principles of classified collection and qualitative treatment, its classification is unreasonable due to its wide variety. With the application of various new technologies, new processes, and new materials in the modern electroplating industry, the pollutants in electroplating wastewater have become increasingly complex. Currently, the classification of electroplating wastewater in my country needs to be clarified and unreasonable. Some areas are divided into 3 to 5 categories. Some areas even reach more than ten categories, which makes the treatment and reuse of electroplating wastewater more complex, and the treatment cost rises (John et al. 2016, Hackbarth et al. 2016).

Lower Reuse Rate of Electroplating Wastewater Treatment

Driven by cleaner production, the recycling rate of electroplating wastewater has been dramatically improved, especially with new technologies such as membrane treatment, nano-filtration, and ion exchange, which have also improved the level of electroplating wastewater treatment (Scarazzato et al. 2017, Van 2018). However, on the whole, the recycling rate of electroplating wastewater in my country is low, especially since the treatment of the organic matter in electroplating wastewater could be better. Although modern electroplating wastewater treatment and reuse technology has made significant progress in the treatment of metal ions, the stability of the wastewater treatment and reuse device could be better. It is challenging to meet the requirements of industrialized sewage standards (Quiton et al. 2022).

Lower Rate of Reuse Up to Standard of Electroplating Wastewater Treatment

With the promulgation and implementation of a series of rules and regulations, such as the “Emission Standard of Electroplating Pollutants” and “Emission Standard of Electroplating Water Pollutants,” the discharge of electroplating pollutants has made significant progress compared with the original (Zhang et al. 2018). However,

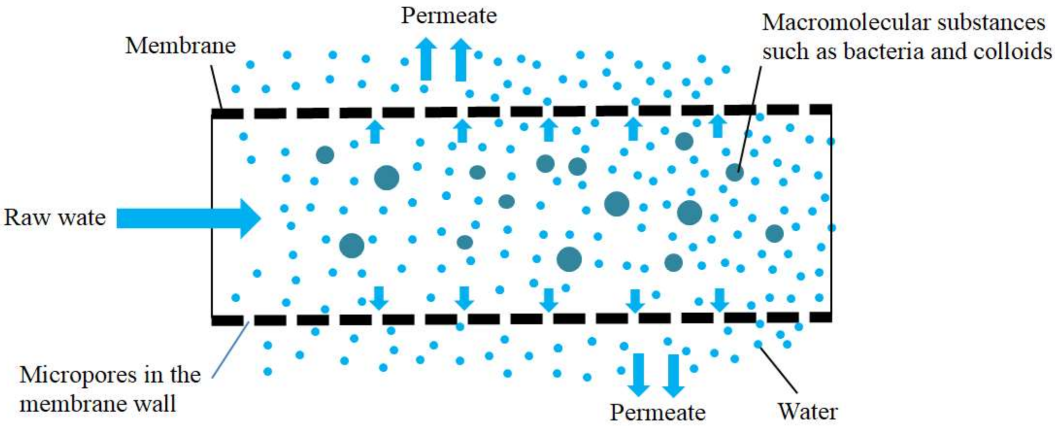


Fig. 4: Membrane separation process principle.

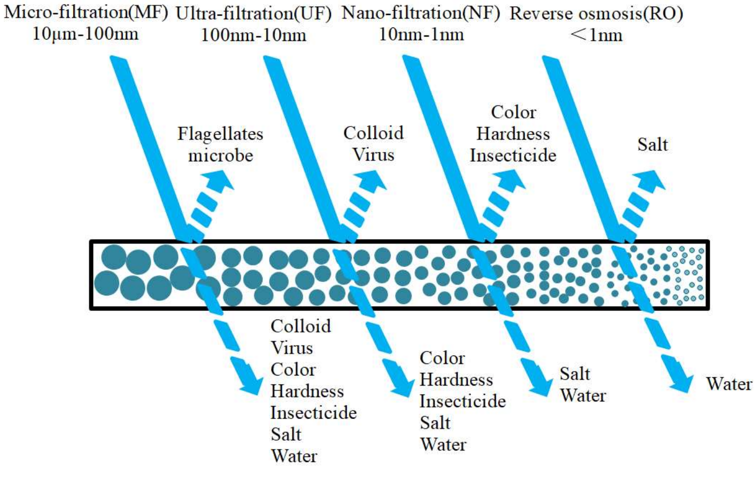


Fig. 5: The filtration process of several common filter membranes.

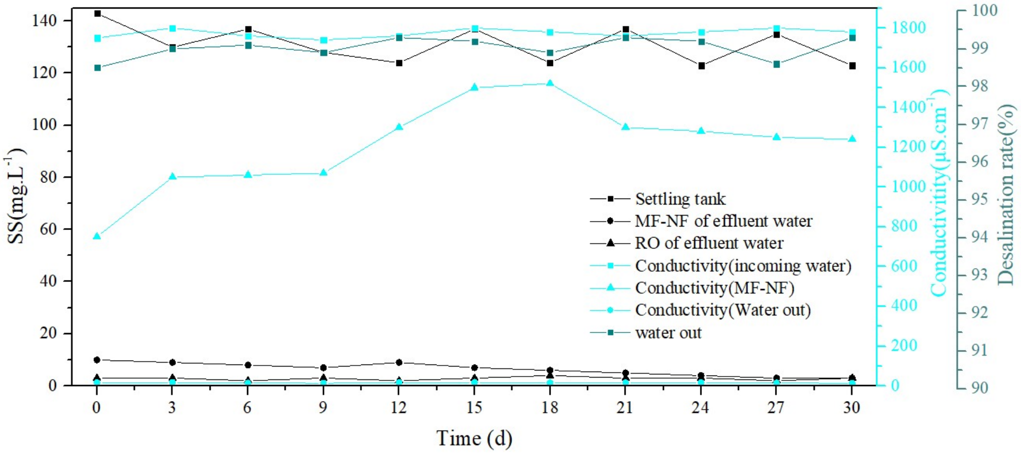


Fig. 6: Effect of membrane treatment system on conductivity, desalination, and SS removal.

many enterprises' electroplating wastewater treatment processes and equipment still need to be improved to meet the standard requirements (Fonseca et al. 2018). For treatment and reuse, defining different treatment water qualities based on the required water quality for reclaimed water reuse may be more meaningful than blindly pursuing sewage standards. Therefore, many enterprises and scholars have also begun to consider reusing the reclaimed water from electroplating wastewater treatment, which may greatly reduce operating treatment costs (Zhang et al. 2018, Van 2018).

Membrane Treatment Technology

The membrane treatment technology of electroplating wastewater uses a membrane with selective permeability to separate the solute and the solute (Fig. 4), the solute and the solvent (water) in the solution under the action of a particular external driving force, to achieve the purpose of purification, concentration, and purification (Fonseca et al. 2018, Van 2018). When the driving force is concentration difference plus chemical reaction, the membrane process is liquid membrane separation; when the driving force is the potential difference, the membrane separation process is electrodialysis; when the driving force is a pressure difference, the membrane separation process is micro-filtration, ultra-filtration, reverse osmosis, nano-filtration (Moslehyani et al. 2019, Park et al. 2018).

The characteristics of membrane treatment technology include separation effects reaching the nanometer level, low process energy consumption, easy maintenance and high reliability of equipment, small equipment footprint, and no introduction of other chemical substances in the material being treated during the process, preventing secondary pollution (Bankole et al. 2017, Ahsan & Imteaz 2019).

In recent years, with the development of electroplating wastewater membrane treatment technology and new discharge standards, a single membrane treatment technology can no longer fulfill the current requirements for electroplating wastewater treatment. As a result, more methods or process combinations are employed in integrated forms to treat electroplating wastewater (Ahsan & Imteaz 2019, Lakhotia et al. 2019). The mainstream membrane treatment technologies include nano-filtration, ultra-filtration, micro-filtration, reverse osmosis, ceramic, and biological membranes. The filtration processes of several standard filter membranes are illustrated in Fig. 5.

Nano-filtration Membrane

Nano-filtration is a membrane separation technology between ultra-filtration and reverse osmosis. The pore size is generally 10 to 1 nm. It is a functional semipermeable membrane that allows solvent molecules or some low molecular weight solutes or low valent ions to pass the membrane (Lakhotia et al. 2019). The molecular weight of it intercepts organic matter is about 150-500, the ability to intercept soluble salt is between 2-98%, and the desalination of monovalent anion salt solution is lower than that of high-valent anion salt solution (Ahmadi et al. 2017, Yan et al. 2018).

Park et al. (2018) used an integrated membrane treatment technology of micro-filtration, nano-filtration, and reverse osmosis to treat electroplating wastewater. The results show that when the CODcr value range of electroplating wastewater inlet is between 100-150 mg.L^{-1}, the CODcr of the water sample in the return water storage tank has decreased to below 10 mg.L^{-1} after being treated by the integrated membrane system (Yan et al. 2018). Although the water quality of the inlet system fluctuates due to the partial interception effect of the integrated membrane on CODcr, the CODcr value of the return water storage tank can be stabilized below 10 mg.L^{-1}, and the CODcr removal rate can reach about 95% (He et al. 2019, Ya et al. 2018). This shows that the integrated membrane system has certain advantages in CODcr treatment. The average removal rate of SS reached 97.1%, and the desalination rate reached 98% (Fig. 6), meeting the standards for electroplating wastewater reuse.

Gündoğdu et al. (2019) used ultra-filtration, nano-filtration, and reverse osmosis technology to establish a pilot-scale platform for electroplating wastewater treatment. The experimental results show that this technology can concentrate nickel ions in nickel-containing electroplating wastewater 8-10 times and produce water. Through the subsequent supplementary processes such as alkali neutralization and ion exchange, the conductivity of the produced water can reach below 2 μS.cm^{-1}, the heavy metal indicators are not detected, and the TOC is less than 5 mg.L^{-1} (Ya et al. 2018, Hegoburu et al. 2020). Hegoburu et al. (2020) conducted a cross-flow filtration experiment on electroplating wastewater with a new pH-stabilized nano-filtration membrane. The results showed that the new pH-stabilized nano-filtration membrane could remove about 75% of heavy metals when treating acidic electroplating wastewater.

In summary, it can be seen that under the combined process treatment of electroplating wastewater, the heavy metal ions in the water can be significantly reduced, the removal rate of CODcr in the water can reach 95%, the removal rate of SS can reach 97.1%, the desalination rate can reach 98%, and the conductivity of the effluent can reach 2 μS.cm^{-1}, TOC is below 5 mg.L^{-1}, meeting the standards for electroplating wastewater reuse.

Ultrafiltration Membrane

Ultra-filtration membrane is a membrane process between micro-filtration and nano-filtration, and the membrane pore size is between 100 nm and 10 nm (Chew et al. 2018). The ultra-filtration membrane sieving process is driven by the pressure difference on both sides of the membrane, and the ultra-filtration membrane is used as the filter medium. Only water and small molecular substances are allowed to pass through to become permeate. In contrast, substances in the raw solution whose volume is larger than the pore size of the membrane surface are trapped on the liquid inlet side of the membrane and become the concentrated solution, thus realizing the purification, separation, and concentration of the raw solution (Totaro et al. 2017, Zhu et al. 2018).

Shen et al. (2019) used the "chemical precipitation-tubular ultra-filtration" combined process to treat copper and total phosphorus in pyrophosphate copper-plating wastewater. The results showed that the dosage of calcium hydroxide was 1.25 g.L^{-1}, the stirring time was 24 min, and when the stirring speed was 150 rpm, the operating pressure was 0.15 MPa (Zhu et al. 2018). The flow rate on the membrane surface was 2.5 m.s^{-1}, the stable flux of the membrane was about 700 L/(m^2·h), and the mass concentration of copper in the effluent was stable between 0.2 and 0.3 mg.L^{-1}, the mass concentration of total phosphorus is stable between 0.2 and 0.4 mg.L^{-1}, all of which meet the requirements of effluent standards (Fig. 7) (Oden & Sari-Erkan 2018, Chen et al. 2018).

Sabeen et al. (2019) used the loading flocculation-ultra-filtration -reverse osmosis process to treat printed circuit board (PCB) wastewater containing high concentrations of heavy metal ions. When the dosage is 1.0 mg.L^{-1}, and the stirring speed is 250 r.min^{-1}, the experimental results show

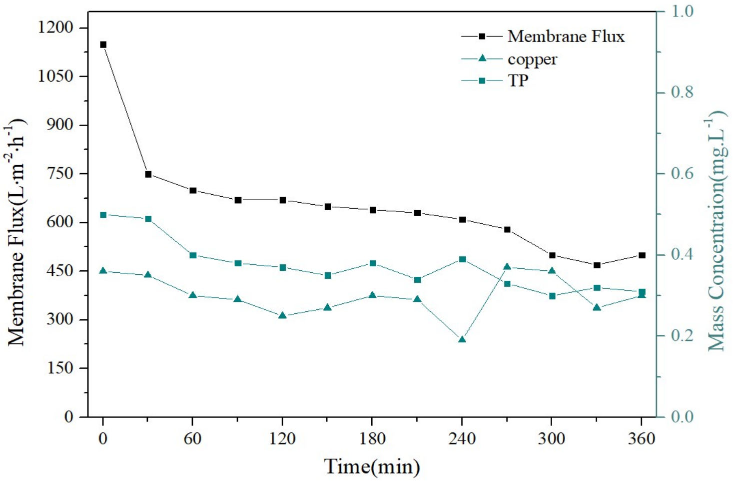


Fig. 7: Membrane flux and effluent quality under continuous operation.

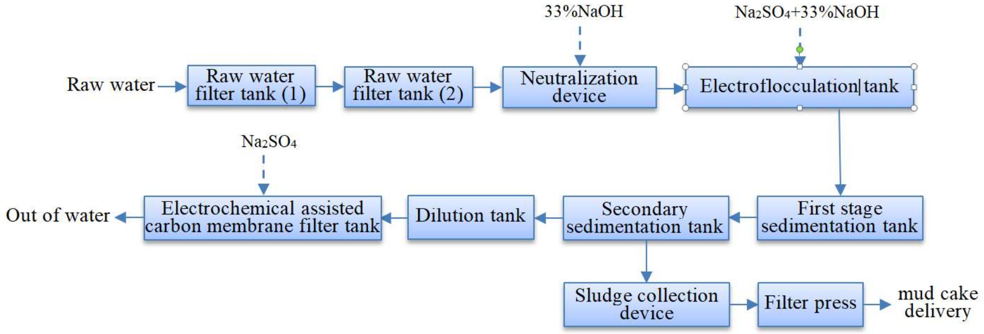


Fig. 8: Electroplating wastewater treatment process.

that the Cu^{2+} and Ni^{2+} concentrations in the effluent are 0.025 $mg.L^{-1}$ and 0.022 $mg.L^{-1}$, and the removal rates are 90.7% and 90.1%, the highest desalination rate can reach 97.6% (Tezcan et al. 2017).

In summary, it can be seen that when using ultrafiltration membranes to treat electroplating wastewater, it is generally necessary to combine other processes for treatment, such as chemical precipitation tube ultrafiltration process, loaded flocculation ultrafiltration reverse osmosis process, etc. The treatment effect of electroplating wastewater using a single ultrafiltration membrane is poor, especially for the removal of heavy metals, which is very limited. However, when the combined process is used to treat electroplating wastewater, when the operating conditions are suitable, the heavy metal ions in the water will be greatly removed, and the desalination rate is also high. The treated wastewater is easy to reach the effluent standard.

Micro-filtration Membrane

The micro-filtration membrane can retain particles between 10 and 0.1μm, allowing macromolecules and dissolved solids (inorganic salts) to pass through while retaining suspended solids, bacteria, and large molecular weight colloids (Chen et al. 2018).

Chowdhury et al. (2018) employed an electrochemically assisted carbon membrane for removing organic matter in electroplating wastewater. The process flow is illustrated in Fig. 8 (Bhateria & Dhaka 2017, Thamaraiselvan et al. 2018). Experimental results demonstrated that the effluent's COD content was 54 $mg.L^{-1}$, and the effluent's Zn^{2+} concentration and COD index met the standard for electroplating pollutant discharge.

Li et al. (2023) conducted an industrial treatment test on electroplating wastewater using a combination of acid-base neutralization precipitation, membrane separation, facultative membrane bioreactor, and reverse osmosis processes. The results demonstrate that the process is feasible and stable, with effective treatment outcomes (Thamaraiselvan et al. 2018, Aslam et al. 2018). The treatment effects of each process section are presented in Table 1 (Kim et al. 2018). Without adding coagulants and flocculants, the effluent consistently meets the electroplating pollutant discharge standards requirements. Simultaneously, heavy metal resources, such as Cu and Ni in the sludge, can be recovered, significantly reducing the costs of chemicals and sludge disposal. The treatment cost per ton of wastewater is approximately 19.1 Yuan, offering economic and environmental benefits (Aslam et al. 2018).

At present, the dual membrane method MF+RO is the most mainstream method for treating electroplating wastewater using membrane separation. The ion retention rate of RO membrane is generally higher than 96% under normal working conditions, which electroplating enterprises highly favor. However, due to the susceptibility of RO membranes to various pollution factors and their high requirements for influent water, direct passage through RO membranes can easily cause membrane blockage, which limits the efficiency and service life of the entire membrane system in treating and reusing electroplating wastewater. So, in the front end of the RO membrane system, an MF membrane system is used to pre-treat the influent water of the reverse osmosis membrane so that the wastewater meets the influent requirements of the reverse osmosis membrane. After that, it is pressurized to remove heavy metal ions through the reverse osmosis membrane system, which can better achieve the expected treatment and reuse effect.

Reverse Osmosis Membrane

Reverse osmosis, also referred to as hyperfiltration, features a membrane structure with a thin, dense layer (0.1-1.0 μm) on the surface and a porous support layer (100-200 μm) beneath the surface layer (Badruzzaman et al. 2019). This membrane separation operation uses pressure difference as the driving force to separate the solvent from the solution. Pressure is applied to the feed liquid on one side of the

Table 1: Treatment effect of each process section.

Process unit	Influent concentration [mg.L^{-1}]					Effluent concentration [mg.L^{-1}]					Removal rate (%)
	COD_{Cr}	Total Cyanide (CN$^-$)	Total nickel	Total copper	Total Silver	COD_{Cr}	Total Cyanide (CN$^-$)	Total nickel	Total copper	Total Silver	
Nickel-containing wastewater pre-separation system	40	-	25	-	-	39	-	5	-	-	2.5(COD) 80(Total nickel)
Nickel-containing wastewater membrane separation system	39	-	5	-	-	38	-	0.5	-	-	2.6(COD) 90(Total nickel)
Acid copper wastewater pre-separation system	15	-	-	100	-	14	-	-	5	-	6.7(COD) 95(Total copper)
Acid copper wastewater membrane separation system	14	-	-	5	-	13	-	-	0.5	-	7.1(COD) 90(Total copper)
Silver-containing wastewater membrane separation system	250	25	-	-	40	240	0.3	-	-	3	4(COD),98.8(CN$^-$) 92.5(Total silver)
Silver-containing wastewater ion exchange system	240	0.3	-	-	3	236	0.3	-	-	0.01	1.7(COD),0(CN$^-$) 99.7(Total silver)
Cyanide-containing wastewater pre-separation system	250	25	-	60	-	240	2	-	4	-	4(COD),92(CN$^-$) 93.3(Total copper)
Cyanide-containing wastewater membrane separation system	240	2	-	4	-	236	0.3	-	0.5	-	1.7(COD),85(CN$^-$) 87.5(Total copper)
Biochemical treatment system	208	0.06	0.07	0.1	0.0005	40	0.06	0.07	0.1	0.0005	80.8(COD),0(CN$^-$), 0(Total nickel),0(Total copper), 0(Total silver)
RO system concentrate	40	0.06	0.07	0.1	0.0005	66.7	0.1	0.12	0.17	0.0008	-
Emission limit [mg.L^{-1}]	-	-	-	-	-	80	0.3	0.5	0.5	0.3	-

membrane; when the pressure surpasses its osmotic pressure, the solvent will permeate against the natural flow direction. Reverse osmosis occurs on the membrane's low-pressure side, while concentration occurs on the high-pressure side (Qin et al. 2019, Senusi et al. 2018).

Sanmartino et al. (2017) designed a chemical pretreatment reverse osmosis membrane and evaporative crystallization process to treat electroplating wastewater based on the water quality and quantity characteristics. Following the project's stable operation, the mass concentration of Cr^{6+} in the pretreatment system effluent can be as low as 0.13 mg.L^{-1}, producing approximately 225 tons of recycled water daily with a conductivity of 424 µs.cm^{-1} (Table 2) (Senusi et al. 2018, Rathna et al. 2019). The treatment cost per ton of wastewater is about 9.7 Yuan, offering good economic benefits, stable system operation, and a high degree of automation, ultimately achieving zero discharge of electroplating wastewater (Rathna et al. 2019, Abdel-Fatah 2018).

Fujioka et al. (2018) analyzed the source and content

Table 2: Pretreated effluent.

	pH	7.5	8.0	7.0	7.5	7.5
Pretreatment system effluent	Cr^{6+}[mg.L^{-1}]	0.19	0.15	0.16	0.16	0.13
	CN$^-$[mg.L^{-1}]	0.21	0.17	0.19	0.15	0.14
Reuse system effluent	Water production [m^3·h^{-1}]	25.5	24.7	25.0	25.3	25.5
	Conductivity [µS.cm^{-1}]	562	643	424	513	438
	TDS[mg.L^{-1}]	525	589	467	534	307

of wastewater from enterprises, applied chemical methods to treat various types of wastewater containing chromium, nickel, and cyanide, and used reverse osmosis membrane separation technology to reuse backwater (Rajoria et al. 2021). The controller controls the wastewater treatment center system of automatic dosing of each treatment unit. The operation process is stable and controllable, and the real-time operation data can be directly transmitted to the environmental protection management department, which meets the requirements of clean production and realizes the purpose of energy saving and emission reduction of the enterprise (Mokhtar et al. 2018, Giwa et al. 2019).

In summary, due to the mature development of reverse osmosis membrane equipment and technology, the treatment effect of electroplating wastewater by reverse osmosis membrane is good, especially for the removal rate of heavy metals and TDS in water. The TDS removal rate is stable at over 94%, and the cost of wastewater treatment is also low. This indicates that reverse osmosis is a key step in removing heavy metals and TDS in electroplating wastewater. However, during normal operation of reverse osmosis cleaning conditions, the membrane inside the reverse osmosis component may be contaminated by inorganic salt scale, microorganisms, colloidal particles, and insoluble organic substances. These pollutants deposit on the surface of the membrane, resulting in a decrease or simultaneous deterioration of the standardized production water flow rate and system desalination rate. Timely cleaning is necessary.

Ceramic Membrane

The ceramic membrane separation process is a "cross-flow filtration" form of fluid separation process: the raw material liquid flows at high speed inside the membrane tube, and under pressure driving, the clarified permeate containing small molecular components penetrates the membrane vertically outward. The turbid concentrated solution containing large molecular components is intercepted by the membrane, thereby achieving the purpose of separation, concentration, and purification of the fluid (Giwa et al. 2019, Abdel-Fatah 2018).

Samaei et al. (2018) treated electroplating wastewater with electro-flocculation and ceramic membrane in small and pilot-scale experiments. The results of electro-flocculation and ceramic membrane experiments in pilot-scale experiments are shown in Fig. 9 (Tao et al. 2022, Zsirai et al. 2018, Davoodbeygi et al. 2023). The test results show that the optimum pH value of the ceramic membrane for treating electroplating wastewater is 10-10.5, and the optimum operating pressure is 3 MPa. This method has a good removal effect on chromium, nickel, copper, and zinc (Zsirai et al. 2018). The removal rate has reached more than 95%, and the final effluent complies with the discharge standard in "Emission Standard of Electroplating Pollutants."

Davoodbeygi et al. (2023) constructed a Fenton oxidation-activated carbon adsorption-ceramic membrane filtration coupling process. The results showed that this technology's removal rate of COD and TOC was stable at about 29.6% and 18.0%, and the removal rate of turbidity reached more than 84.3% (Dharupaneedi et al. 2019). After treatment, the concentrations of COD and TOC in the effluent are less than 52.1 mg.L^{-1} and 18.0 mg.L^{-1}, and the turbidity of the effluent is far less than 0.5 NTU (Fig. 10) (Zhang et al. 2018).

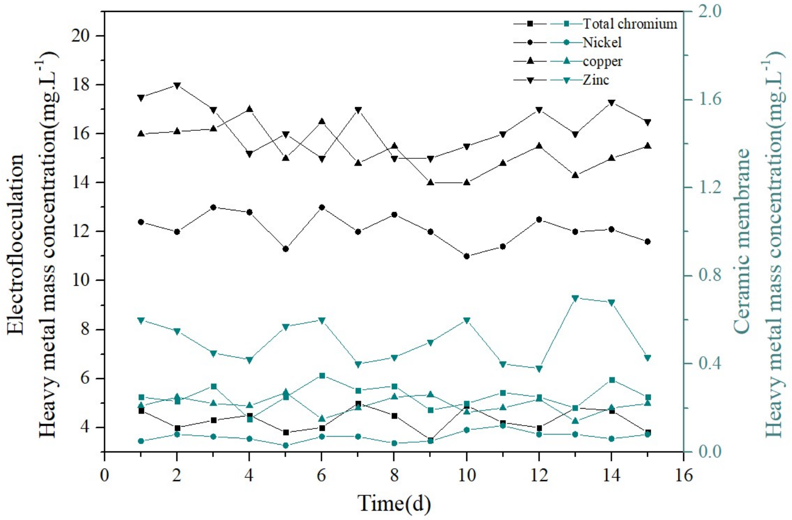


Fig. 9: Pilot test of electro-flocculation and Ceramic membrane pilot test.

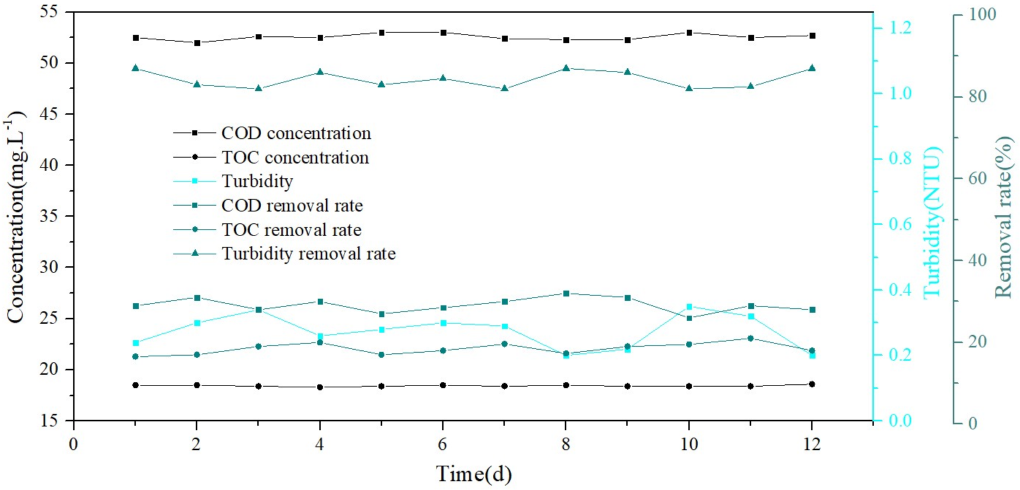


Fig. 10: Concentration and removal rate of COD, TOC, and turbidity.

Wang (2018) used ceramic membrane, reverse osmosis, and multi-effect evaporation technology to reduce the content of hexavalent chromium in the effluent to 0.01 $mg.L^{-1}$, the content of nickel to 0.11 $mg.L^{-1}$, and the content of iron to 0.28 $mg.L^{-1}$, the manganese content was reduced to 0.08 $mg.L^{-1}$, the COD and TDS in the effluent were reduced to 8.5 $mg.L^{-1}$ and 136 $mg.L^{-1}$, the turbidity of the effluent was reduced to 0.3 NTU (Table 3) (Nidhi et al. 2019, Bai et al. 2019, Bhateria & Dhaka 2017). It complies with the cooling water reuse standard in the "Design Specification for Urban Sewage Reuse," The reverse osmosis concentrated water is evaporated by a high-efficiency evaporator, realizing zero discharge of electroplating wastewater treatment (Bhateria & Dhaka 2017).

Bukhari et al. (2017) used silicon carbide flat membranes to treat electroplating wastewater. The results show that silicon carbide flat membrane has good acid and alkali, oil, and corrosion resistance and can effectively reduce suspended solids and some organic matter in electroplating wastewater (Pronk et al. 2019). The removal rate of suspended solids and turbidity is as high as 99%, and the flat membrane effectively removes COD while reducing operating costs (Zhao et al. 2019).

In summary, it can be seen that when using ceramic membranes to treat electroplating wastewater, it is generally necessary to combine other processes for treatment, such as electrocoagulation and ceramic membrane processes, Fenton oxidation activated carbon adsorption ceramic membrane filtration coupling process, ceramic membrane reverse osmosis multi-effect evaporation process, silicon carbide flat membrane, etc. When a single ceramic membrane is used to treat electroplating wastewater, the effluent quality is greatly affected by the reaction pH value, and its treatment effect is very limited. However, when combined processes are used to treat electroplating wastewater, most of the heavy metals such as hexavalent chromium, nickel, iron, and manganese in the effluent are removed, and the COD and turbidity in the effluent are also greatly reduced.

Biofilm Membrane

Biofilm treatment technology is a method of organic sewage treatment using microorganisms (i.e., biofilms) attached to the surface of particular solid objects (Desmond et al. 2018).

Rahman et al. (2021) used the micro-electrolysis-DMBR process to treat electroplating wastewater. The removal rates of hexavalent chromium and nickel were 99.34% and 99.14%, the removal rates of COD and ammonia nitrogen were 94.75% and 90.22% (Fig. 11), and the effluent reached "Emission Standards for Electroplating Pollutants"

Table 3: Effluent quality of ceramic membrane and first stage reverse osmosis process.

Project	pH	Turbidity (NTU)	Chroma (time)	[$mg.L^{-1}$]						
				COD	NH_3-N	TDS	Iron	Chromium	Nickel	Manganese
Ceramic membrane effluent	7.8	0.3	0.2	70.5	0.066	3412	0.25	0.01	0.05	0.09
Reverse osmosis effluent	7.7	n.d.	n.d.	8.5	0.012	136	n.d.	n.d.	0.01	n.d.

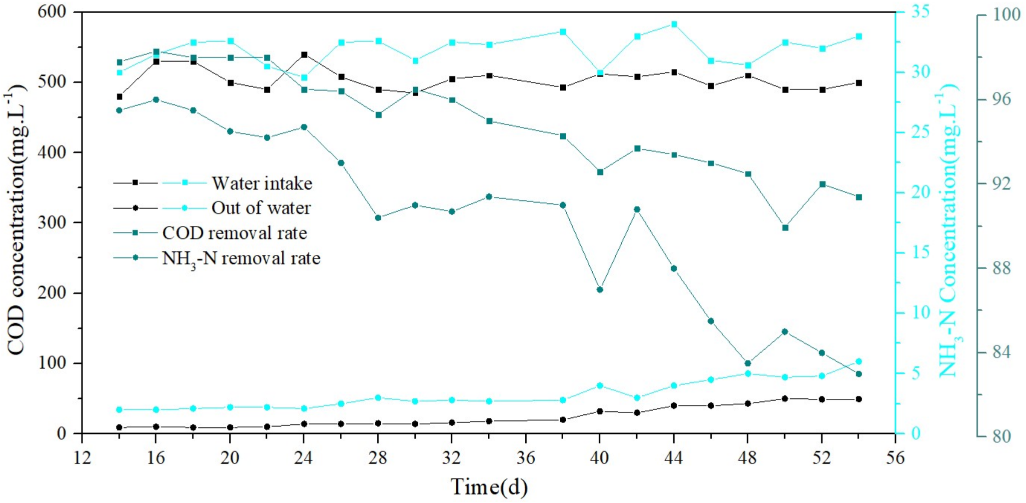


Fig. 11: Removal of COD and NH3-N in Micro electrolysis-DMBR.

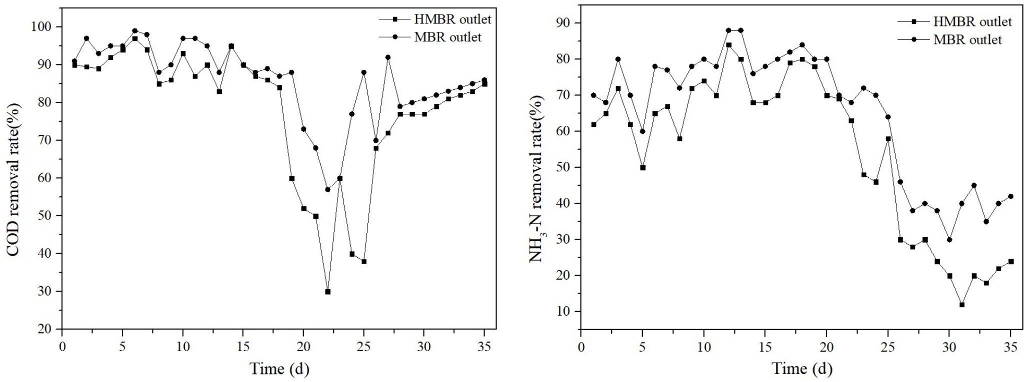
(GB21900-2008) (Guan et al. 2017).

Xiong et al. (2023) used a green emulsion liquid film to recover zinc from electroplating water. The experimental conditions were that the pH value of the environment was 3.8, the volume content of surfactant was 4%, the equivalent concentration of the internal phase was 1.61 N, and the concentration of zinc was 3.8 (Noah et al. 2018, Bratovcic et al. 2022). When the concentration is 742 mg.L^{-1}, the emulsion volume ratio of the external phase is 0.94, and the carrier concentration is 8.9%, the maximum recovery rate of zinc can reach 97.4%. Z Rujia (2020) added a sedimentation tank at the MBR tank's front end during the electroplating wastewater treatment system transformation, which alleviated the problem of membrane blockage. The system can maintain stable operation for at least 24 h after online backwashing. After three weeks of operation, the comprehensive wastewater MBR The daily average fluxes of MBR and mixed wastewater are 12.56 L/(m^2.h) and 10.49 L/(m^2.h), respectively, and the average daily running time of 21 h can meet the requirements of treated water volume and discharge water quality (Goswami et al. 2019, Sari Erkan et al. 2018).

Li-Kun et al. (2018) used the suspended carrier composite MBR process (HMBR) to run in parallel with the normal MBR process, represented by heavy metal ions Cu^{2+}, Ni^{2+}, and Cr (VI). They focused on the electroplating synthesis of the two processes under the impact of different concentrations of heavy metals (Tan et al. 2019, Bortoluzzi et al. 2017). The effect of wastewater efficiency and microbial activity, as well as the control effect of carrier intervention on membrane fouling and the impact on the diversity of microbial populations, the experimental results show that under the impact of Cu^{2+}, Ni^{2+}, Cr(VI) concentrations of 5-30 mg.L^{-1}, HMBR the removal rate of COD and NH_3-N by the process is over 60% and 40%, while the removal rate of COD and NH_3-N by the standard MBR process is over 30% and 15% (Fig. 12) (Wang & Wang 2019). Rajasimman et al. (2021) applied biological methods to treat zinc-nickel alloy electroplating wastewater. The COD removal rate could reach 91.45%.

In summary, the treatment of electroplating wastewater by biofilm mainly relies on artificially cultivated composite functional bacteria, which have electrostatic adsorption, enzyme catalytic conversion, complexation, flocculation, co-precipitation, and pH buffering effects. The outer shell of microbial functional bacteria carries a certain negative charge and is easy to absorb metal ions with positive charges. The bacterial micelles themselves have strong biological flocculation, which can adsorb and chelate heavy metals on their surface. Functional bacteria first reduce C^{6+} in wastewater to Cr^{3+}, and then Cr^{3+}, zinc, nickel, copper, and lead plasma are adsorbed and synthesized into clusters by the bacteria. After solid-liquid separation, the wastewater is discharged or reused to meet the standards, while heavy metal ions precipitate into sludge.

In summary, membrane treatment technology for electroplating wastewater has been extensively employed in laboratory experiments, pilot tests, and industrial applications. The most widely used membrane treatments include nano-filtration membranes, ultra-filtration membranes, micro-filtration membranes, reverse osmosis membranes, ceramic membranes, and biological membranes. For treating electroplating wastewater, nano-filtration membranes can achieve an average removal rate of 97.1% for suspended



(a) (b)

Fig. 12: (a) COD removal effect of HMBR and MBR processes at each stage; (b) NH3-N removal effect of HMBR and MBR processes at each stage.

solids, a desalination rate of 98%, reduce effluent turbidity to below 0.1 NTU, attain a conductivity of below 2 μS.cm^{-1} for the produced water, achieve a TOC of less than 5 mg.L^{-1}, and remove approximately 75% of heavy metals in wastewater. When ultra-filtration membranes treat electroplating wastewater, the total phosphorus concentration in the effluent remains stable between 0.2 and 0.4 mg.L^{-1}. The Cu^{2+} and Ni^{2+} concentrations in the effluent can be reduced to 0.025 mg.L^{-1} and 0.022 mg.L^{-1}, respectively, with removal rates reaching 90.7% and 90.1%, and the highest desalination rate of effluent can reach 97.6%. When microfiltration membranes treat electroplating wastewater, the COD content of the effluent can be reduced to 54 mg.L^{-1}. The effluent's Zn^{2+} concentration and COD index meet the emission standards, and the water treatment cost per ton is approximately 19.1 Yuan. When reverse osmosis membranes treat electroplating wastewater, the mass concentration of Cr^{6+} in the effluent can be as low as 0.13 mg.L^{-1}, producing about 225 tons of recycled water daily with a conductivity of 424 μS.cm^{-1}, and the water treatment cost per ton is around 9.7 Yuan. When ceramic membranes treat electroplating wastewater, hexavalent chromium, nickel, iron, and manganese in the effluent are reduced to 0.01 mg.L^{-1}, 0.11 mg.L^{-1}, 0.28 mg.L^{-1}, and 0.08 mg.L^{-1}, respectively. The COD and TDS in the effluent are reduced to 8.5 mg.L^{-1} and 136 mg.L^{-1}, the effluent turbidity is reduced to 0.3 NTU, and the removal rate of suspended solids and turbidity reaches as high as 99%. When biofilm treats electroplating wastewater, hexavalent chromium and nickel removal rates reach 99.34% and 99.14%. COD and ammonia nitrogen removal rates reach 94.75% and 90.22%, and the effluent meets discharge requirements. Simultaneously, the maximum zinc recovery rate can reach 97.4%.

When using membrane treatment technology to treat electroplating wastewater, the effluent quality is better than traditional processes, with strong impact resistance, and can significantly reduce the concentration of pollutants. However, it also has certain drawbacks, such as high membrane cost, easy occurrence of membrane pollution, and high energy consumption. Therefore, the future development of membrane treatment technology in the field of electroplating wastewater treatment must focus on the research and development of membrane materials while formulating a series of feasible laws and regulations and treated standards, standardizing the management of the electroplating wastewater treatment industry, and deepening research and innovation of technology.

CONCLUSIONS AND FUTURE PERSPECTIVES

Membrane treatment technology is currently the predominant approach in electroplating wastewater treatment and plays a crucial role in the overall process. This paper outlines four prospects for the advancement of membrane treatment technology for electroplating wastewater:

(1) As the electroplating industry continues to develop, the complexity of electroplating wastewater increases. Developing more scientific, safe, and reasonable classification and treatment methods is essential. Electroplating wastewater should be divided into categories based on specific physical or chemical properties, and appropriate treatment processes should be designed accordingly. Combining various membrane processes for different treatment methods can enhance the overall efficiency of wastewater treatment.

(2) The high salt content of electroplating wastewater poses a challenge, as it can lead to membrane fouling during treatment. Although physicochemical methods are employed in the pretreatment stage to reduce salt

content, finding rapid, safe, and environmentally friendly solutions to prevent membrane clogging remains a significant challenge.

(3) Different types of electroplating wastewater should be treated with various membranes according to their primary components and characteristics. Establishing a relationship between wastewater types and membrane selection can lead to more effective and reasonable treatment approaches.

(4) At present, the membrane treatment technology for electroplating wastewater mainly focuses on the direct removal of heavy metals, thereby transferring pollutants and waste resources. However, there is little research on the classification and recovery of heavy metals in wastewater after membrane technology treatment. Membrane treatment technology should be used to concentrate and collect heavy metals and other pollutants in electroplating wastewater and then further classify and recover heavy metals from the concentrated wastewater, thereby promoting resource recovery and sustainable development.

(5) The development direction of membrane separation technology will be more green and environmentally friendly. In the process of treating electroplating wastewater, physical methods are mainly used to collect and concentrate heavy metal ions in the wastewater, which can increase the recovery rate of metal ions. Whether it is aerospace research, land construction, or domestic exploration, membrane separation technology is indispensable. In today's society, various countries are striving to improve their membrane separation technology capabilities. From biofilms to polymer membranes and liquid membranes, membrane separation technology research has become a high-tech research type.

(6) Membrane technology in the field of electroplating wastewater treatment will soon become a cutting-edge topic of key development at home and abroad. Therefore, higher requirements have been put forward for membrane materials, especially to manufacture membrane materials that are suitable for the environmental protection industry with high strength, long lifespan, pollution resistance, and high throughput. The research on membrane separation technology is also advancing day by day. With the increasing improvement of regulations and standards, the continuous maturity of membrane technology, and the continuous reduction of costs, membrane technology will appear to be more advanced in technology and more widely used in applications.

ACKNOWLEDGEMENT

The present work is sponsored by the Science Foundation of Shaanxi Province of China (No.2022JQ-327), the Special Scientific Research Program of the Education Department of Shaanxi Province (No.22JK0425) and the school-level fund project of Xi'an Aeronautical University (No. 2021KY1203).

List of abbreviations	
Nano-filtration	NF
Ultra-filtration	UF
Micro-filtration	MF
Reverse osmosis	RO
Electrodialysis	ED
Polyethylene terephthalate	PET
M-phenylenediamine	MPD
Trimethylene chloride	TMC
Polyacrylamide	PAM
Polyaluminum chloride	PAC
Nanometer	Nm
Chemical oxygen demand	COD
Suspended matter	SS
Total organic carbon	TOC
Total phosphorus	TP
Printed circuit board	PCB
Total Cyanide	CN
Total dissolved solids	TDS
Nephelometric Turbidity Units	NTU
No detection	n.d.
Dynamic membrane bio-reactor	DMBR
Membrane Bio-Reactor	MBR
Hybrid membrane bioreactor	HMBR

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