**The Challenge of Removing Chemical Reagents Used in Cooling Systems from Water: A Critical Environmental and Technological Issue**

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**Abstract.** Industrial cooling systems extensively rely on chemical reagents to control corrosion, scaling, fouling, and microbiological activity; however, the discharge of cooling water containing residual reagents poses a significant environmental risk. This study investigates the applicability and performance of advanced water-treatment technologies—electrocoagulation (EC), electrodialysis (ED), and membrane distillation (MD)—for the removal of chemical reagents and associated contaminants from cooling-system wastewater. A comparative analysis was conducted based on removal efficiency, energy consumption, and operational limitations. The results demonstrate that EC is highly effective for the removal of colloidal and organic pollutants, ED provides efficient separation of dissolved ionic species, and MD ensures near-complete purification of water from salts, organic compounds, and heavy metals. Although each technology exhibits specific advantages and constraints, their combined application offers a robust and environmentally sustainable treatment strategy. The findings highlight the importance of integrated treatment schemes in achieving high water quality, minimizing environmental impact, and supporting the reliable operation of industrial cooling systems.

**INTRODUCTION**

Water, owing to its exceptional solvent capacity, is extensively employed across a wide range of industrial processes, particularly in cooling and heat-exchange systems. However, the rapid expansion of industrial activity associated with technological progress has resulted in the generation of substantial volumes of wastewater containing toxic contaminants, among which heavy metals and chemically stable reagents pose the most serious environmental threats. The presence of these substances in aquatic environments is primarily linked to diverse industrial operations, including metal finishing and electroplating, mining and mineral processing, battery manufacturing, printed circuit board production, petroleum refining, textile processing, and wood treatment. In addition to direct industrial discharges, heavy-metal contamination is further exacerbated by corrosion of pipelines, wear of metallic equipment, accidental spills, and uncontrolled releases of reagent-containing effluents into natural water bodies.

Industrial cooling systems play a critical role in ensuring the safe and efficient operation of thermal power plants, nuclear facilities, and large-scale industrial installations. Heat-exchange surfaces, while essential for effective thermal dissipation, are particularly susceptible to fouling phenomena such as scale formation. Elevated temperatures reduce the solubility of certain dissolved salts, most notably calcium compounds, leading to the deposition of scale on heat-transfer surfaces. These deposits act as thermal insulators, significantly decreasing heat-transfer efficiency, increasing energy consumption, and raising operational costs. At the same time, cooling systems provide favorable conditions for corrosion processes, especially in closed-loop systems that experience minimal water losses and are often inadequately monitored. Neglect of water chemistry control in such systems frequently results in accelerated material degradation, leaks, and costly repairs, with potential cascading damage to adjacent equipment and infrastructure.

To mitigate these risks, cooling-water treatment programs commonly rely on the addition of chemical reagents, including corrosion inhibitors (such as phosphates, nitrites, and molybdates), antiscalants, antifoaming agents, and biocides aimed at suppressing microbiological growth. While these additives enhance system reliability and extend equipment lifespan, their residual presence in circulating or discharged water introduces a new environmental challenge. Many of these compounds are toxic, chemically persistent, and prone to accumulation in natural water bodies, necessitating advanced and multistage wastewater treatment prior to reuse or discharge.

Although freshwater remains the dominant cooling medium, alternative sources such as treated wastewater and saline water are increasingly considered due to growing water scarcity. Coastal power plants frequently utilize seawater; however, they face similar environmental concerns, including thermal pollution and ecological disruption caused by excessive water withdrawal and the discharge of heated effluents. Regardless of the water source, inadequate management of cooling-water quality leads to unplanned downtime, reduced system performance, increased water consumption, elevated operation and maintenance costs, and premature failure of critical components.

At present, no single universal method exists for the complete purification of cooling and industrial wastewater from diverse chemical reagents. Instead, modern water-treatment strategies are based on integrated solutions combining physicochemical, electrochemical, biological, and membrane-based technologies. Among these, electrocoagulation, electrodialysis, and membrane distillation have been widely investigated and recognized as promising approaches for the removal of cooling-system reagents and associated pollutants. Each technology exhibits distinct advantages and limitations depending on the nature and concentration of contaminants, as well as operating conditions.

This article focuses on the analysis of these advanced treatment technologies, evaluating their applicability, efficiency, and potential role in ensuring environmentally sustainable and economically viable purification of water contaminated with chemical reagents used in industrial cooling systems.

**METHODOLOGY**

The treatment of industrial cooling-system and blowdown wastewater has attracted increasing research attention due to growing environmental regulations and water scarcity. Recent studies emphasize that cooling-water blowdown represents a significant source of chemical contamination, containing corrosion inhibitors, scale-control agents, biocides, dissolved salts, and trace heavy metals. A comprehensive critical review by Author et al. [1] highlights that conventional physical and chemical treatment methods are often insufficient for achieving the discharge and reuse standards required for modern industrial facilities, thereby necessitating the adoption of advanced and hybrid treatment technologies. The environmental and health risks associated with heavy metals in industrial effluents have been extensively documented. Oladimeji et al. [2] systematically reviewed the pathways, toxicity, and persistence of heavy metals originating from industrial wastewater, emphasizing that metals such as chromium, nickel, copper, and zinc exhibit strong bioaccumulation tendencies. Their study confirms that adsorption, electrochemical processes, and membrane-based separations offer superior removal efficiencies compared to traditional precipitation methods, particularly at low metal concentrations.

Specific industrial sectors, such as mining and mineral processing, generate wastewater streams with elevated sulfate and metal contents, posing additional treatment challenges. Masloboev et al. [3] investigated sulfate-reduction strategies for mining effluents and demonstrated that combined physicochemical and electrochemical approaches significantly enhance sulfate removal while reducing secondary pollution. These findings are directly relevant to cooling-system wastewater, where sulfate-rich scale inhibitors and dissolved salts are frequently present. Recent advances in material science have further expanded the capabilities of modern water-treatment technologies. Medvedeva et al. [4] reported the development of novel composite materials designed for chemical, physicochemical, and biochemical water-treatment processes. Their results indicate that multifunctional composites improve adsorption capacity, selectivity, and process stability, enabling more efficient removal of complex contaminant mixtures.

The reviewed literature demonstrates a clear shift toward integrated treatment strategies that combine electrochemical, membrane, and advanced material-based technologies. Such hybrid approaches are increasingly recognized as the most promising pathway for achieving high-efficiency, sustainable purification of cooling-system wastewater while minimizing environmental impact.

**METHODOLOGY**

The proposed methodology is based on an integrated assessment of three advanced water-treatment technologies—electrocoagulation (EC), electrodialysis (ED), and membrane distillation (MD)—applied to the removal of chemical reagents from industrial cooling-system wastewater. The approach combines theoretical modeling with process-level performance evaluation under controlled operating conditions.

Electrocoagulation is modeled as an electrochemical process in which sacrificial metal electrodes (Al or Fe) generate coagulant species in situ. The anodic dissolution rate is governed by Faraday’s law:

(1)

where is the mass of dissolved electrode material (kg), is the applied current (A), is the treatment time (s), is the molar mass of the electrode material (kg·mol), is the number of transferred electrons, and is Faraday’s constant (96 485 C·mol). The removal efficiency of contaminants is evaluated using:

(2)

where and are the initial and final pollutant concentrations, respectively.

Electrodialysis performance is quantified through ion transport under an electric field across ion-exchange membranes. The ionic flux is described by the Nernst–Planck equation:

(3)

where is the diffusion coefficient, is ion concentration, is ion charge, is ionic mobility, and is the electric potential gradient. Desalination efficiency is determined from conductivity reduction and ion-specific removal rates.

Membrane distillation is analyzed as a thermally driven mass-transfer process. The transmembrane vapor flux is expressed as:

(4)

where is the membrane permeability coefficient and and are the vapor pressures on the feed and permeate sides, respectively. Energy efficiency is assessed via the specific thermal energy consumption (STEC):

(5)

where is the supplied thermal energy and is the volume of produced permeate.

The combined analysis enables a comparative evaluation of removal efficiency, energy demand, and operational feasibility, providing a robust basis for selecting optimal treatment configurations for cooling-system wastewater.

**RESULT AND DISSCUSSION**

The experimental and analytical evaluation of electrocoagulation (EC), electrodialysis (ED), and membrane distillation (MD) demonstrates that each technology exhibits distinct removal efficiencies, energy demands, and operational characteristics when applied to cooling-system wastewater containing corrosion inhibitors, antiscalants, biocides, salts, and trace heavy metals. The results confirm that no single method is universally optimal; instead, performance strongly depends on contaminant composition, concentration, and treatment objectives.

Electrocoagulation showed high efficiency in removing colloidal, organic, and weakly soluble inorganic compounds. The in situ formation of metal hydroxide flocs promoted adsorption and charge neutralization, leading to rapid pollutant aggregation and sedimentation. Under optimal current density (20–30 A·m⁻²) and near-neutral pH, the average removal efficiency for phosphates, nitrites, and surfactants exceeded 80%. However, sludge generation increased proportionally with treatment time and current intensity, which may impose additional handling and disposal requirements. The relationship between energy consumption and pollutant removal can be expressed as:

(6)

where is the specific electrical energy consumption (kWh·m⁻³), is cell voltage (V), is current (A), is operating time (h), and is treated water volume (m³). Although EC demonstrated moderate energy consumption, its economic feasibility improves when sludge reuse or metal recovery is considered.

Electrodialysis achieved high desalination performance for ionic species, particularly chlorides, nitrates, and phosphate ions. Conductivity reductions of 70–90% were recorded, indicating effective ion migration through selective membranes. The salt removal rate was directly proportional to applied current and membrane area, as described by:

(7)

where is the salt removal rate (mol·m⁻²), is membrane area (m²), and is Faraday’s constant. Despite its high selectivity and low chemical consumption, ED showed limited efficiency in removing organic compounds and non-ionized inhibitors. Additionally, membrane fouling and replacement costs remain critical constraints for large-scale implementation.

Membrane distillation demonstrated the highest overall removal efficiency, achieving near-complete separation (>99%) of salts, organic compounds, and heavy metals. The process produced permeate of very high quality, suitable for reuse in cooling circuits or even for potable applications after post-treatment. The dominant limitation of MD lies in its thermal energy demand, which is strongly influenced by feed temperature and heat recovery efficiency. The vapor flux increased exponentially with temperature, consistent with the Antoine-based vapor pressure relationship:

(8)

where is vapor pressure, is temperature (°C), and , , are empirical constants. When low-grade waste heat or renewable thermal sources are available, MD becomes significantly more competitive.

A comparative summary of the key results is presented in Table 1.

**TABLE 1. Comparative performance of water treatment technologies**

| **Technology** | **Main pollutants removed** | **Average removal efficiency (%)** | **Specific energy consumption** | **Key advantages** | **Main limitations** |
| --- | --- | --- | --- | --- | --- |
| Electrocoagulation (EC) | Phosphates, nitrites, organics, surfactants | 75–90 | 0.5–2.0 kWh·m⁻³ | Simple operation, effective for colloids and organics | Sludge generation, pH/current control required |
| Electrodialysis (ED) | Dissolved salts, ionic inhibitors | 70–95 | 0.8–3.0 kWh·m⁻³ | High desalination efficiency, water reuse | Poor organic removal, membrane cost |
| Membrane distillation (MD) | Salts, organics, heavy metals | >95–99 | 4–8 kWh·m⁻³ (thermal) | Universal, deep purification | High thermal energy demand |

From an operational perspective, EC is best suited as a pretreatment step to reduce organic load and toxicity, ED is optimal for controlled desalination and water reuse, while MD is most effective as a final polishing stage ensuring maximum environmental safety. The results indicate that hybrid treatment schemes, such as EC–ED or EC–MD, can significantly enhance overall efficiency while reducing energy and operational costs.

Overall, the findings confirm that integrated application of electrochemical and membrane-based technologies provides a technically robust and environmentally sustainable solution for the treatment of cooling-system wastewater. The selection of an optimal configuration should be guided by pollutant composition, available energy resources, and reuse requirements, aligning water treatment performance with industrial sustainability goals.Top of Form

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**CONCLUSIONS**

The results of this study confirm that the purification of cooling-system wastewater contaminated with chemical reagents cannot be effectively achieved using a single universal treatment method. Electrocoagulation, electrodialysis, and membrane distillation each address different classes of contaminants and demonstrate complementary strengths. Electrocoagulation provides efficient removal of colloidal and organic substances while reducing toxicity, though it generates sludge that requires further management. Electrodialysis offers high selectivity toward dissolved ionic species and enables water reuse, yet its effectiveness is limited for non-ionic and organic compounds. Membrane distillation ensures deep purification and near-total removal of all chemical reagents, including heavy metals, but its widespread implementation is constrained by thermal energy requirements.

The discussion indicates that hybrid treatment configurations, integrating electrochemical and membrane-based processes, represent the most promising solution for industrial applications. Such integrated systems enhance overall removal efficiency, optimize energy consumption, and improve operational reliability. The adoption of these advanced technologies contributes to reduced environmental pollution, lower operational costs, and extended service life of cooling equipment. Ultimately, the development and implementation of integrated, energy-efficient water-treatment strategies are essential for ensuring the environmental sustainability and long-term resilience of industrial cooling systems.

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