
Advanced Treatment of High-Salinity Wastewater in the Coal Chemical Industry: A Survey

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Abstract

The coal chemical industry, a key player in global energy production, faces significant environmental challenges due to the generation of high-salinity wastewater. This survey paper explores advanced treatment methods, emphasizing the integration of advanced oxidation processes (AOPs) and membrane technology to achieve effective desalination and zero liquid discharge. The industry's wastewater, characterized by high salinity and toxic components, poses ecological risks, necessitating innovative solutions beyond conventional methods. AOPs, particularly sulfate radical-based processes, show promise in degrading persistent pollutants, while novel membrane technologies, including graphene-based materials, offer enhanced separation efficiency. The integration of these technologies with electrochemical and thermal methods can optimize treatment outcomes, addressing the limitations of individual approaches. Furthermore, the survey highlights the potential of feedback-driven resource allocation and machine learning to enhance system adaptability and efficiency. Despite advancements, challenges such as membrane fouling and economic feasibility persist, underscoring the need for continued research into scalable and sustainable solutions. By leveraging cutting-edge materials and processes, the coal chemical industry can achieve more effective wastewater management, ensuring compliance with environmental standards and supporting long-term sustainability. Future research should focus on optimizing the design and integration of graphene-based membranes, exploring innovative brine management solutions, and addressing economic constraints to advance the field of wastewater treatment.

1 Introduction

1.1 Significance of the Coal Chemical Industry

The coal chemical industry plays a crucial role in the global economy, primarily through its substantial contributions to energy production and its support of various industrial processes [1]. Beyond energy, understanding the intricate interactions within its operational systems is essential for addressing environmental challenges [2]. Optimizing resource allocation in large-scale operations is vital for enhancing efficiency and maintaining economic viability. Thus, the coal chemical industry is integral to the global economic landscape, necessitating advanced management and technological innovations to tackle its environmental and operational challenges effectively.

1.2 Environmental Challenges

The coal chemical industry encounters significant environmental challenges, particularly concerning high-salinity wastewater management, which poses ecological risks to aquatic ecosystems due to its toxic components. Improper disposal can lead to severe environmental degradation, highlighting the urgent need for advanced treatment technologies [3].

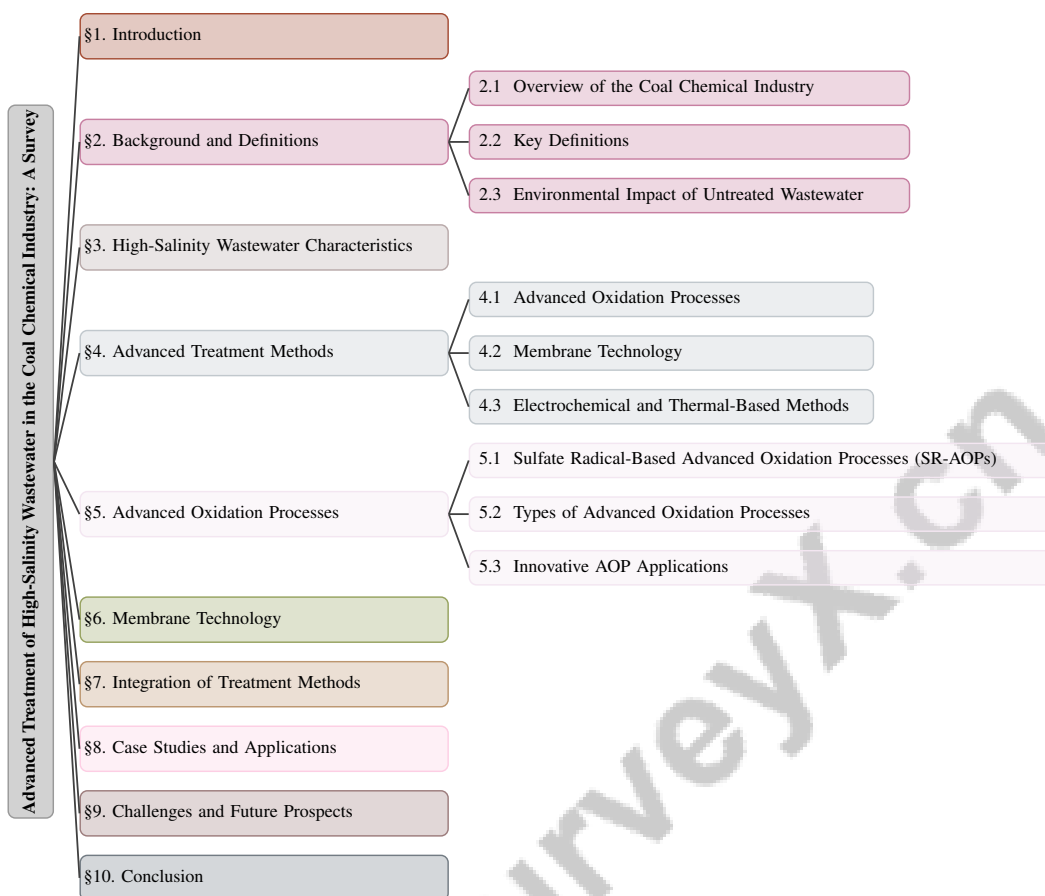


Figure 1: chapter structure

The complexity of managing high-salinity wastewater is exacerbated by variable workloads and resource availability [4]. Conventional treatment methods often fail to adequately address these challenges, emphasizing the necessity for innovative solutions capable of managing high salt concentrations and associated contaminants [1]. The presence of persistent organic pollutants, such as synthetic dyes and heavy metals, further complicates treatment, as traditional methods struggle to eliminate these substances.

Technical challenges in implementing effective treatment methods in high-temperature and high-pressure environments, particularly in thermal desalination processes, underscore the complexity of wastewater management [5]. The interaction of materials like graphene oxide with water significantly influences treatment efficiency and contaminant removal [6].

These environmental and economic challenges are not unique to the coal chemical industry; they also affect other sectors, such as shale gas extraction [7]. A comprehensive approach integrating advanced treatment technologies and innovative management strategies is essential for sustainable industrial practices and minimizing environmental impact.

1.3 Necessity for Advanced Treatment Methods

The management of high-salinity wastewater in the coal chemical industry necessitates advanced treatment methods, as conventional techniques like reverse osmosis and electrodialysis struggle with complex wastewater compositions and high energy demands. Current desalination technologies face significant challenges regarding energy efficiency and separation effectiveness, making the exploration of innovative solutions imperative [8].

The energy-intensive nature of existing methods for heavy metal removal and desalination limits their sustainability and feasibility for large-scale applications [9]. Zero Liquid Discharge (ZLD) systems

present a promising approach for managing brine and recovering freshwater, yet their high energy consumption and carbon emissions hinder practical implementation [7, 10]. The ineffectiveness of current desalination methods, which either consume excessive energy or are prohibitively costly, further underscores the urgent need for advanced treatment solutions.

Moreover, the inability of conventional wastewater treatment methods to eliminate refractory organic pollutants necessitates exploring advanced oxidation processes utilizing natural minerals [11]. This survey aims to highlight scientific advancements in wastewater treatment through advanced oxidation processes (AOPs) as sustainable solutions to the increasing demand for clean water and effective wastewater management [12]. The challenges in understanding energy consumption across various desalination processes further emphasize the need for advanced treatment methods [13].

Innovative treatment processes, such as the $O_3 + MnO_x/GAC + H_2O_2$ system, demonstrate potential in simultaneously mineralizing and dehalogenating high-salinity dye wastewater, underscoring the necessity for continued research and development in this area [14]. Adopting such advanced methods is critical for transitioning to a circular water economy, prioritizing water reuse and the utilization of nontraditional water sources [15]. By leveraging machine learning and feedback-driven resource allocation mechanisms, the coal chemical industry can enhance the adaptability and efficiency of its treatment systems, ensuring compliance with environmental regulations and promoting sustainable industrial practices [16].

1.4 Structure of the Survey

This survey is structured to address key aspects of advanced treatment for high-salinity wastewater in the coal chemical industry. The introduction outlines the industry's significance and the environmental challenges associated with high-salinity wastewater, emphasizing the need for advanced treatment methods. The background section provides a comprehensive overview of the coal chemical industry's processes, key definitions, and the environmental impact of untreated wastewater.

The characteristics of high-salinity wastewater are explored in detail, focusing on its composition, the limitations of conventional treatment methods, and the associated environmental and health implications. The section on advanced treatment methods examines the efficacy of advanced oxidation processes, membrane technology, and electrochemical and thermal-based techniques. A detailed discussion on advanced oxidation processes highlights sulfate radical-based processes, various types, and innovative applications.

The role of membrane technology is scrutinized, addressing different types of membranes, challenges such as fouling and scaling, and recent advancements. The integration of treatment methods is discussed, illustrating how combining advanced oxidation processes (AOPs), particularly sulfate radical-based AOPs, with membrane technology can significantly enhance wastewater treatment outcomes. This synergy improves the removal of micropollutants and organic matter while extending the lifespan of membrane systems, rendering treated wastewater suitable for industrial, agricultural, and domestic reuse. Multi-objective optimization frameworks further support this integration, facilitating efficient treatment strategies [17, 18].

The survey also presents case studies and real-world applications, including electro-sorption process simulation, nanofluidic and electro-osmotic applications, and the potential of protocell technology in environmental treatment. Finally, the survey addresses the challenges and future prospects of implementing advanced treatment methods, outlining technical challenges, future research directions, and regulatory and environmental considerations. The conclusion synthesizes the principal findings, emphasizing the critical role of advanced oxidation processes (AOPs) in wastewater treatment as a sustainable solution to global water scarcity. It identifies promising areas for future research, including the integration of AOPs with other treatment technologies and the economic viability of large-scale implementations, thereby underscoring the potential for innovation in water reclamation and resource management [19, 20, 12, 21, 18]. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Overview of the Coal Chemical Industry

The coal chemical industry plays a vital role in the global economy, influencing energy production and various industrial processes. It is characterized by complex operations that produce high-salinity wastewater containing contaminants such as heavy metals like copper, necessitating effective treatment strategies [8, 9]. Processes like coal gasification and liquefaction are energy-intensive, contributing to saline effluents and highlighting the demand for innovative treatment technologies [2]. The energy demands of brine crystallization and zero liquid discharge (ZLD) systems complicate wastewater management due to their high energy consumption [22].

Decentralized water treatment solutions offer flexibility and efficiency, particularly in smaller-scale operations, as viable alternatives to traditional centralized methods [15]. For example, solar-driven ZLD desalination systems target high-salinity wastewater from industries like shale gas extraction, demonstrating potential for cross-sector applications [7]. Furthermore, cation intercalation desalination (CID) methods, using cation intercalation host compounds with ion-exchange membranes, represent efficient desalination advancements [23].

As freshwater resources diminish and demand rises, the coal chemical industry must adopt advanced treatment technologies to mitigate environmental impacts and ensure sustainability [24]. Evaluations of distributed systems and workload patterns further optimize resource allocation, enhancing adaptability to evolving environmental conditions [16].

2.2 Key Definitions

Zero Liquid Discharge (ZLD) is a wastewater management strategy aimed at eliminating liquid waste discharge, ensuring complete water recovery and minimizing contaminants. This involves various brine disposal methods, such as surface water discharge, sewer discharge, deep-well injection, evaporation ponds, and land application, each with distinct environmental and economic impacts [19]. The use of synthetic graphene oxide materials in solar desalination technologies is particularly relevant to ZLD, offering innovative approaches to enhance water recovery [25].

Advanced Oxidation Processes (AOPs) are crucial for treating high-salinity wastewater by generating reactive species that degrade complex organic pollutants resistant to conventional methods. These processes address contaminants of emerging concern and ensure compliance with stringent regulations [12]. The application of -graphyne-4 membranes in desalination exemplifies AOPs' potential for high water permeability and salt rejection, enhancing treatment effectiveness [26].

Membrane technology, employing semi-permeable membranes to separate contaminants, includes reverse osmosis, which removes dissolved salts and impurities under pressure [10]. Osmosis, driven by solute concentration differences, is fundamental to membrane technology [3]. Innovations in synthetic graphene oxide materials in membrane technology promise enhanced desalination efficiency, particularly for achieving ZLD [25].

Advanced membrane technologies, such as flow-electrode capacitive deionization (FCDI) and membrane electrode assemblies (MEAs), are significant for treating high-salinity wastewater by improving ion removal efficiency [27]. Integrating these with other desalination processes driven by pressure, electric fields, and heat provides a comprehensive framework for advanced treatment methods [13]. The theory of electrolyte transport in charged nanopores, based on a force-flux framework incorporating Onsager symmetry, offers insights into advanced mechanisms like electrochemical deionization [28]. Additionally, deionization shock waves driven by bulk electroconvection in circular channels under over-limiting current conditions present a novel approach to enhancing desalination efficiency [29].

These definitions establish a foundational understanding of the technologies and processes involved in the advanced treatment of high-salinity wastewater, emphasizing the necessity for ongoing innovation and optimization [30].

2.3 Environmental Impact of Untreated Wastewater

Untreated high-salinity wastewater discharge from the coal chemical industry poses significant environmental risks due to high concentrations of salts and contaminants that can severely affect aquatic ecosystems. This leads to altered water chemistry, disrupting aquatic life and degrading water quality [19]. High salinity can cause osmotic stress on aquatic organisms, reducing biodiversity and potentially leading to ecosystem collapse.

Economic and environmental challenges associated with brine disposal exacerbate the situation. High desalination costs and inefficiencies in current treatment processes hinder effective solutions, amplifying the environmental impact of untreated wastewater [15]. Brine disposal, often a by-product of desalination, introduces risks like soil and water salinization, threatening agricultural productivity and freshwater resources [30].

Environmental concerns related to brine disposal are compounded by high energy consumption and membrane fouling issues in conventional desalination technologies [10]. These challenges highlight the need for sustainable and cost-effective brine treatment and disposal methods that minimize environmental pollution while maximizing freshwater recovery. The absence of such solutions not only threatens the environment but also limits the coal chemical industry's ability to mitigate its ecological footprint.

In recent years, the management of high-salinity wastewater has emerged as a critical concern, particularly within the coal chemical industry. This paper reviews the existing literature on this topic, highlighting the intricate challenges posed by such wastewater. Figure 2 illustrates the characteristics and challenges associated with high-salinity wastewater, detailing its composition and the limitations of conventional treatment methods. The figure emphasizes key components, including the complex matrix of pollutants and the ecological and health risks associated with inadequate treatment, thereby underscoring the urgent need for advanced and sustainable treatment solutions. By integrating these insights, we can better understand the multifaceted nature of the issue and the imperative for innovative approaches in wastewater management.

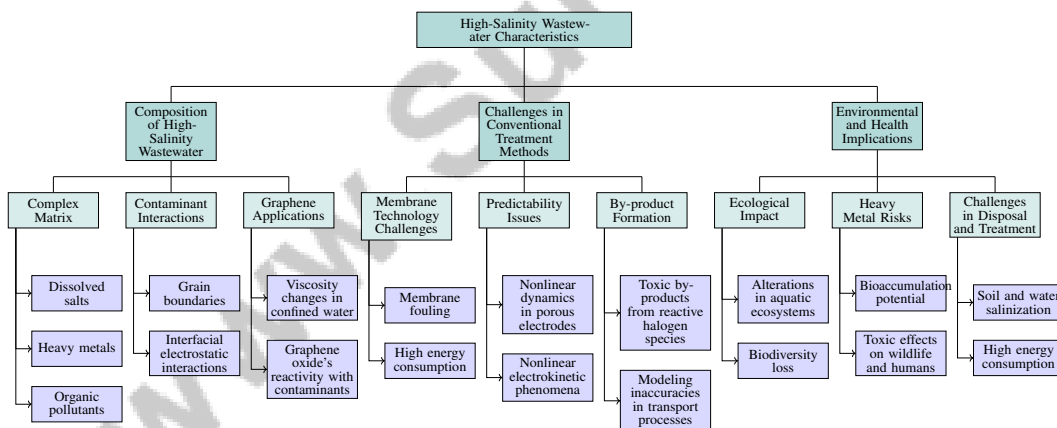


Figure 2: This figure illustrates the characteristics and challenges associated with high-salinity wastewater from the coal chemical industry, detailing its composition, the limitations of conventional treatment methods, and the environmental and health implications. Key components include the complex matrix of pollutants, the challenges in conventional treatment technologies, and the associated ecological and health risks, emphasizing the need for advanced and sustainable treatment solutions.

3 High-Salinity Wastewater Characteristics

3.1 Composition of High-Salinity Wastewater

High-salinity wastewater from the coal chemical industry is characterized by a complex matrix of dissolved salts, heavy metals, and organic pollutants, complicating treatment processes due to persistent contaminants like copper, which pose environmental risks and challenge conventional removal methods [9]. Figure 3 illustrates the primary components of high-salinity wastewater,

emphasizing the presence of dissolved salts and metals, organic pollutants, and the role of graphene in filtration technologies. The desalination performance is further complicated by factors such as grain boundaries and interfacial electrostatic interactions, which influence contaminant stability and behavior [31]. Understanding these interactions is crucial for developing effective treatment technologies.

The viscosity of water confined between graphene layers changes significantly when capillary sizes fall below 2 nm, affecting transport and separation processes in filtration systems [32]. Graphene oxide's net negative charge in water offers potential applications in filtration and remediation due to its reactivity with various contaminants [6]. Continued research into the chemical composition and behavior of high-salinity wastewater is essential for developing more effective and sustainable treatment solutions.

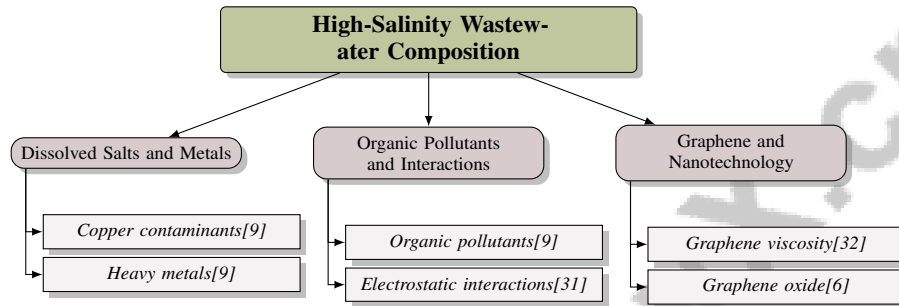


Figure 3: This figure illustrates the primary components of high-salinity wastewater, emphasizing the presence of dissolved salts and metals, organic pollutants, and the role of graphene in filtration technologies.

3.2 Challenges in Conventional Treatment Methods

Conventional treatment methods for high-salinity wastewater face significant challenges due to the effluents' complex composition and high energy requirements. Traditional membrane technologies, such as reverse osmosis, are often hindered by membrane fouling, leading to increased energy consumption and operational costs, limiting their efficiency [25]. Inefficiencies in brine disposal exacerbate the environmental and economic burdens associated with these technologies.

Optimizing energy efficiency in desalination processes is challenging due to varying mechanisms and separation outcomes [13]. The nonlinear dynamics of capacitive charging and desalination in porous electrodes complicate treatment predictability [33]. Additionally, nonlinear electrokinetic phenomena in complex porous structures, especially under ion concentration polarization and over-limiting current conditions, remain challenging to predict, impacting conventional treatment effectiveness [34].

Reactive halogen species formation during catalytic ozonation can lead to more toxic by-products, complicating effective wastewater treatment [14]. Transitioning from atomistic dynamics to continuum hydrodynamics under nonequilibrium conditions introduces inaccuracies in modeling transport processes, diminishing the reliability of conventional methods [35]. These challenges highlight the need for advanced methods, such as innovative membrane technologies and advanced oxidation processes, which have shown potential in enhancing pollutant removal efficiency and addressing issues like membrane fouling and toxic by-product formation [17, 19, 14, 12].

3.3 Environmental and Health Implications

High-salinity wastewater from the coal chemical industry poses significant environmental and health risks due to its complex composition, including high levels of dissolved salts, heavy metals, and organic pollutants. Discharge into natural water bodies can lead to severe ecological consequences, such as alterations in aquatic ecosystems and biodiversity loss [19]. Elevated salinity levels can induce osmotic stress in aquatic organisms, causing physiological disruptions and potential mortality, thereby threatening aquatic community stability.

The presence of heavy metals, particularly copper, presents long-term environmental hazards due to their persistence and bioaccumulation potential, resulting in toxic effects on wildlife and humans who consume contaminated water or organisms [9]. Chronic exposure to heavy metals is associated with various health issues, including neurological and developmental disorders.

Environmental impact is further intensified by challenges in brine disposal, which can lead to soil and water salinization, adversely affecting agricultural productivity and freshwater availability [30]. High energy consumption and membrane fouling issues associated with conventional desalination technologies also contribute to the environmental footprint of high-salinity wastewater treatment, underscoring the need for more sustainable and efficient solutions [10]. Additionally, the formation of reactive halogen species during certain treatment processes can generate more toxic by-products, posing further risks to environmental and human health [14]. These challenges underscore the urgent need for advanced treatment methods that effectively mitigate the environmental and health implications of high-salinity wastewater, ensuring the protection of ecosystems and public health while supporting the sustainable development of the coal chemical industry.

4 Advanced Treatment Methods

Category	Feature	Method
Advanced Oxidation Processes	Machine Learning Techniques	GNOF[36]
	Integrated Treatment Strategies	MDC-ED[9], AHOA[1]
Membrane Technology	Advanced Membrane Materials	BFN[37], nano-rGO[38], MD[39]
	Simulation and Analysis Models	CSPM[40]
Electrochemical and Thermal-Based Methods	High-Salinity and High-Temperature Operations	FCDI[41], ISCA[5]
	Electrochemical Transport Mechanisms	SED[42], RBIP[43], NEMD[44]
	Solar and Light-Based Enhancements	3D-SC[22], PTU[24]

Table 1: This table provides a comprehensive overview of advanced treatment methods for high-salinity wastewater, categorized into Advanced Oxidation Processes, Membrane Technology, and Electrochemical and Thermal-Based Methods. It highlights specific features and methods employed within each category, along with relevant references, showcasing the integration of innovative techniques and materials to enhance treatment efficacy and sustainability.

Advancing treatment methodologies for high-salinity wastewater requires innovative strategies to enhance efficacy and sustainability. Table 1 presents a detailed summary of various advanced treatment methods for high-salinity wastewater, highlighting key features and techniques across different categories. Additionally, Table 3 offers a comprehensive comparison of various advanced treatment methods for high-salinity wastewater, emphasizing their primary mechanisms, efficiency, and associated challenges. This section examines Advanced Oxidation Processes (AOPs), which are recognized for their ability to degrade persistent organic pollutants through highly reactive radicals, addressing the complex challenges in wastewater treatment within the coal chemical industry.

4.1 Advanced Oxidation Processes

Advanced oxidation processes (AOPs), particularly sulfate radical-based AOPs (SR-AOPs), are crucial for treating high-salinity wastewater by effectively eliminating micropollutants and offering a robust alternative to conventional methods [9]. The high reactivity of sulfate radicals facilitates the oxidation of diverse contaminants, enhancing treatment outcomes for complex wastewater streams.

AOPs are categorized based on oxidant generation and activation, enabling evaluations of energy efficiency and operational characteristics [12]. This includes electrochemical advanced oxidation processes (EAOPs), which involve direct and indirect methods where hydroxyl radical generation is vital for pollutant degradation [11]. Such classifications optimize AOP applications for specific wastewater characteristics.

Innovative strategies, such as integrating catalytic ozonation with AOPs, improve organic pollutant degradation while managing by-product formation [13]. Utilizing nickel hexacyanoferrate (NiHCF) electrodes in continuous flow capacitive deionization (CDI) systems exemplifies advancements in desalination, enhancing salt removal and reducing costs [9].

Theoretical frameworks predicting electrosorption behavior in flow-through electrode CDI cells provide insights into interactions between contaminants and treatment media [1]. Unified non-

equilibrium simulation methodologies offer a comprehensive understanding of transport phenomena across nanoporous membranes, facilitating simultaneous application of multiple driving forces [36].

The application of AOPs, especially SR-AOPs, in the coal chemical industry holds significant promise for effective wastewater treatment. By leveraging sulfate radicals' unique properties and integrating AOPs with advanced technologies, the industry can address high-salinity wastewater challenges, ensuring sustainable practices and regulatory compliance. This approach not only enhances the degradation of refractory organic pollutants with cost-effective catalysts but also strategically addresses energy consumption and resource allocation, promoting a sustainable water treatment framework [13, 11, 15, 12].

4.2 Membrane Technology

Membrane technology is pivotal in treating and desalinating high-salinity wastewater from the coal chemical industry, providing advanced solutions for contaminant separation. Key processes include microfiltration, ultrafiltration, nanofiltration, reverse osmosis (RO), forward osmosis, electrodialysis (ED), and pervaporation, each defined by its operational principles and applications [17]. These methods utilize selective permeability and ion transport dynamics to effectively remove dissolved salts and impurities, facilitating efficient wastewater treatment.

As illustrated in Figure 4, which highlights the key components of membrane technology in wastewater treatment, the figure showcases the primary processes, innovative materials, and challenges associated with this technology, along with strategies for mitigation. Advancements in novel materials, such as nanoporous MoS₂ membranes, enhance water permeability and salt rejection, addressing traditional membrane limitations [39]. Additionally, membranes incorporating nano-sized reduced graphene oxide (nano-rGO) flakes exhibit improved water permeance and ion rejection capabilities, advancing membrane technology further [38].

Despite innovations, membrane technology faces challenges like fouling and scaling, which impair performance and increase costs. Fouling includes biofouling, organic fouling, inorganic scaling, and colloidal fouling, necessitating mitigation strategies to maintain efficiency and longevity [45]. Thermodynamic design and fouling mitigation strategies in membrane distillation are vital for enhancing sustainability in high-salinity wastewater treatment [46].

Electrokinetic transport properties in nano-fluidic devices are significant for advanced treatment methods targeting high-salinity wastewater [4]. The effectiveness of membrane technology is influenced by the relationship between water transport rates and surface properties, as demonstrated in studies involving polyelectrolyte multilayers (PEMs) [37]. Insights from simulating salt separation in nanopores using core-softened potentials contribute to understanding water flux under varying pressures and pore sizes, optimizing membrane processes [40].

Continued advancements in membrane technology are essential for effective high-salinity wastewater treatment in the coal chemical industry. By addressing fouling and scaling challenges while leveraging novel materials and techniques, membrane technology can significantly enhance desalination efficiency, ensuring compliance with environmental standards and supporting long-term industry viability [17].

4.3 Electrochemical and Thermal-Based Methods

Electrochemical and thermal-based methods have emerged as viable solutions for high-salinity wastewater treatment in the coal chemical industry. These approaches utilize advanced mechanisms and specialized materials to enhance desalination efficiency and sustainability, addressing traditional methods' limitations amid increasing water scarcity and demand [47, 17]. Table 2 presents a comparative analysis of electrochemical and thermal-based methods for treating high-salinity wastewater, focusing on their mechanisms, efficiency, sustainability, and scalability challenges.

Shock electrodialysis (ED) represents a significant advancement in electrochemical treatment, using surface conduction and electro-osmotic flow for ionic transport in porous media, enabling continuous deionized water extraction [42]. This technique effectively integrates filtration, separation, and disinfection with deionization, resulting in compact and efficient water purification systems [48]. Flow-electrode capacitive deionization (FCDI) can concentrate brines with NaCl concentrations up to 291.5 g/L while significantly reducing energy demands compared to traditional methods [41].

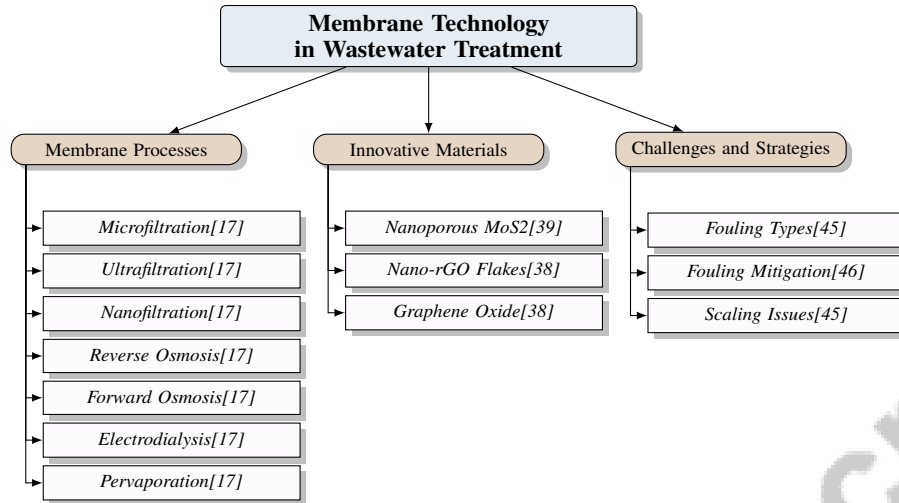


Figure 4: This figure illustrates key components of membrane technology in wastewater treatment, highlighting primary processes, innovative materials, and challenges with strategies for mitigation.

Method Name	Mechanism Type	Efficiency and Sustainability	Scalability Challenges
SED[42]	Electro-osmotic Flow	Ionic Transport Efficiency	Scalability Optimization
FCDI[41]	Capacitive Adsorption Mechanism	Significant Energy Reductions	Increased Overall Resistance
RBIP[43]	Capacitive Ratchet Mechanism	Enhancing Durability Efficiency	Performance Degradation Observed
PTU[24]	Photo-thermal Umbrella	Solar-thermal Efficiency	Initial Capital Costs
3D-SC[22]	Thermal Conductivity	Reduced Energy Consumption	Land Requirements
ISCA[5]	Electrochemical Sensor	Real-time Monitoring	Residual Measurement Artifacts
NEMD[44]	Nemd Simulations	High Permeate Rates	Nanopore Proximity

Table 2: Overview of various electrochemical and thermal-based methods for high-salinity wastewater treatment, highlighting their mechanisms, efficiency, sustainability, and scalability challenges. The table compares different approaches, such as shock electrodialysis and flow-electrode capacitive deionization, in terms of their ionic transport efficiency and energy consumption. It also addresses the scalability issues faced by each method, providing insights into potential improvements for industrial applications.

Furthermore, ambipolar ion pumping ratchets (RBIP) enhance desalination by effectively transporting both cations and anions against concentration gradients, achieving a net ion flux of $0.03 \text{ mol/m}^2\text{s}$, with advantages including durability and efficiency due to the absence of moving parts and redox reactions [43].

In thermal-based methods, membrane distillation (MD) has been explored, though it faces challenges such as low energy efficiency, membrane fouling, and scaling that hinder large-scale deployment [47]. Innovative concepts, such as using a photo-thermal umbrella to convert sunlight into mid-infrared radiation, have been proposed to enhance solar evaporation, potentially improving thermal desalination energy efficiency [24]. A novel 3D solar crystallizer separates light absorption from water evaporation surfaces, enhancing efficiency and mitigating scaling issues [22]. Experimental insights from continuous thermal desalination units operating at temperatures up to 623 K and pressures up to 250 bar using NaCl solutions contribute to understanding the physicochemical processes involved [5].

Exploring electrochemical and thermal-based methods provides valuable insights into alternative treatment strategies for high-salinity wastewater. By addressing energy consumption, scalability, and efficiency challenges, these methods can significantly enhance the sustainability and effectiveness of wastewater treatment in the coal chemical industry. Future research should focus on optimizing these processes, exploring hybrid systems, and investigating their scalability for industrial applications [49]. Furthermore, deriving a global linear-response relation extending the local Onsager matrix to heterogeneous systems can enhance understanding of electrochemical treatment methods [4]. Non-Equilibrium Molecular Dynamics (NEMD) simulations evaluating nanopore proximity's influence on water flux and salt rejection present promising avenues for optimizing membrane designs and improving treatment performance [44].

Feature	Advanced Oxidation Processes	Membrane Technology	Electrochemical and Thermal-Based Methods
Primary Mechanism	Radical Generation	Selective Permeability	Ionic Transport
Efficiency	High Reactivity	Variable BY Method	Energy Intensive
Challenges	Energy Consumption	Fouling And Scaling	Scalability Issues

Table 3: This table provides a comparative analysis of advanced treatment methods for high-salinity wastewater, focusing on Advanced Oxidation Processes, Membrane Technology, and Electrochemical and Thermal-Based Methods. Key features such as primary mechanisms, efficiency, and challenges associated with each method are outlined to highlight their applicability and limitations in the context of wastewater treatment.

5 Advanced Oxidation Processes

Advanced Oxidation Processes (AOPs) are crucial for treating high-salinity wastewater, employing highly reactive species to degrade persistent pollutants and improve treatment efficacy. This section highlights sulfate radical-based AOPs (SR-AOPs), a leading method for managing complex wastewater compositions.

5.1 Sulfate Radical-Based Advanced Oxidation Processes (SR-AOPs)

Sulfate radical-based advanced oxidation processes (SR-AOPs) effectively treat high-salinity wastewater by utilizing sulfate radicals ($SO_4^{\cdot-}$) to degrade a broad spectrum of persistent pollutants. These radicals, generated through thermal, photochemical, and electrochemical processes, offer operational flexibility and superior degradation efficiency [20]. Their high redox potential surpasses hydroxyl radicals, making them effective against recalcitrant compounds in complex wastewater containing heavy metals and organic pollutants [12].

Integrating SR-AOPs with advanced technologies addresses traditional diffusion limitations. For instance, shock electrodialysis enhances ionic transport, improving treatment efficiency alongside SR-AOPs [42]. Innovations in capacitive deionization (CDI) systems, employing carbon nanotube fibers and metal oxides, enhance electrode performance and efficiency [50].

Theoretical insights into osmosis mechanisms support SR-AOP effectiveness in high-salinity wastewater treatment [3]. Studies on pore size variability and network connectivity optimize SR-AOP system design and operation [34]. Molecular dynamics simulations reveal water permeation and ion rejection mechanisms in bicrystalline hBN membranes, highlighting grain boundaries and interfacial electrostatic interactions in SR-AOPs [31]. Research on MoS₂ membranes challenges existing fluid mechanics assumptions, guiding membrane design optimization [44].

SR-AOPs offer promising solutions for high-salinity wastewater in the coal chemical industry. By leveraging sulfate radicals' properties and integrating advanced technologies, the industry can address wastewater challenges, ensuring sustainable practices and regulatory compliance. This approach enhances pollutant degradation and addresses energy consumption and resource allocation issues [51].

5.2 Types of Advanced Oxidation Processes

Advanced Oxidation Processes (AOPs) encompass various methods utilizing reactive species, primarily hydroxyl and sulfate radicals, to degrade complex pollutants. These processes are categorized by radical generation methods, such as catalytic, thermal, or radiation activation, and their mechanisms for enhancing pollutant degradation, including wastewater treatment, disinfection, and micropollutant removal [18, 12]. Key types include photochemical, electrochemical, and catalytic oxidation processes.

Figure 5 illustrates the classification of Advanced Oxidation Processes (AOPs) into these three primary categories: Photochemical, Electrochemical, and Catalytic Oxidation. Each category includes key methods and innovations relevant to wastewater treatment and pollutant degradation, emphasizing their adaptability and efficiency in addressing environmental challenges.

Photochemical AOPs, like UV/H₂O₂ and UV/O₃, use ultraviolet light to activate oxidants, generating radicals that degrade organic contaminants. Efficiency is influenced by functional groups on nanoporous materials' pore edges, affecting water transfer rates and ion rejection efficiencies [52].

Electrochemical AOPs (EAOPs) apply electrical current to produce reactive species at electrode surfaces. Innovations such as flexible, chemically stable carbon fiber fabric improve charge transport and enable thinner ion-exchange membranes [27]. These advancements highlight EAOPs' potential for sustainable high-salinity wastewater treatment.

Catalytic oxidation processes, like Fenton and photo-Fenton reactions, use catalysts to enhance radical generation. The integration of hydrogel-modified evaporation interfaces in membrane technology improves stability and performance in high-salinity environments, addressing challenges associated with traditional membranes [53].

The classification of AOPs underscores their versatility and adaptability in tackling high-salinity wastewater challenges. This classification reflects varying energy efficiencies and operational mechanisms, with sulfate radical-based processes and UV-based photocatalysis recognized for eliminating micropollutants and enhancing disinfection. Advancements in AOP technologies are critical for addressing global water scarcity, making them essential for sustainable wastewater management and resource recovery [20, 12, 45, 17, 18]. By leveraging each type's unique properties, the coal chemical industry can mitigate environmental impacts and enhance water treatment efficiency, ensuring compliance with stringent regulatory standards.

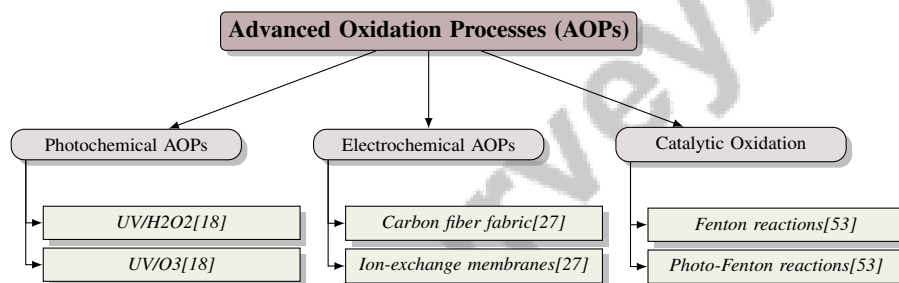


Figure 5: This figure illustrates the classification of Advanced Oxidation Processes (AOPs) into three primary categories: Photochemical, Electrochemical, and Catalytic Oxidation. Each category includes key methods and innovations relevant to wastewater treatment and pollutant degradation, emphasizing their adaptability and efficiency in addressing environmental challenges.

5.3 Innovative AOP Applications

Innovative applications of Advanced Oxidation Processes (AOPs) in the coal chemical industry significantly enhance wastewater treatment efficiency and sustainability. Thermal-driven membrane processes demonstrate remarkable efficiency in water desalination, offering a viable alternative for high-salinity wastewater treatment [8]. The membranes' ability to maintain high performance under challenging conditions underscores their industrial applicability.

The use of synthetic graphene oxide (GO) materials in solar-powered desalination systems represents another advancement in sustainable water treatment. GO's high stability and performance under high-salinity conditions, along with minimal environmental impact, make it an attractive option for the coal chemical industry [25]. This approach enhances desalination efficiency while aligning with the industry's goals of reducing carbon footprint and promoting sustainable practices.

Desalination shocks in microfluidic systems offer innovative wastewater treatment solutions. These systems exploit microstructures to enhance ion separation and pollutant degradation efficiency in high-salinity environments [54]. The application of desalination shocks presents a promising avenue for developing compact and efficient treatment systems tailored to the coal chemical industry's specific needs.

Innovative AOP applications demonstrate their potential to enhance water quality and promote sustainable wastewater reuse by eliminating micropollutants and improving subsequent treatment stages, such as membrane filtration [17, 20, 18, 45]. By integrating novel materials and processes, the

coal chemical industry can achieve more effective and sustainable wastewater management, ensuring compliance with environmental regulations and supporting long-term viability.

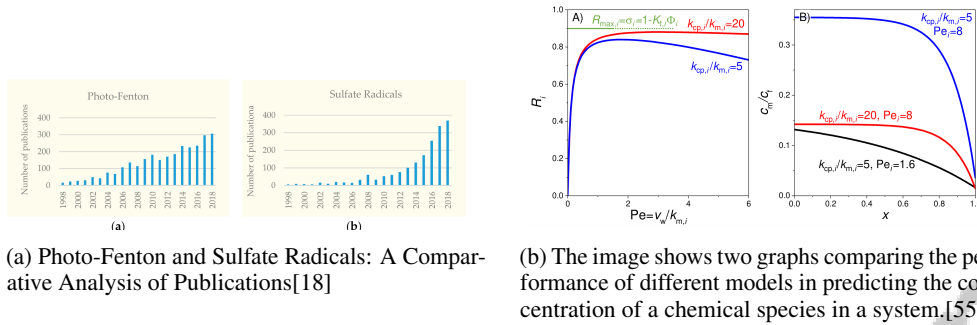


Figure 6: Examples of Innovative AOP Applications

As illustrated in Figure 6, AOPs play a pivotal role in addressing environmental challenges, particularly in water treatment and pollution remediation. The first subfigure, "Photo-Fenton and Sulfate Radicals: A Comparative Analysis of Publications," visually represents the scientific interest in these topics over two decades, highlighting the growing research focus on potent oxidation processes. This analysis underscores the evolving landscape of AOP research, particularly in Photo-Fenton reactions and sulfate radical applications. The second subfigure compares the predictive modeling of chemical species concentrations within a system, showcasing graphs that illustrate model performance variations. Together, these examples highlight innovative applications and ongoing research efforts in AOPs, emphasizing their significance in advancing environmental science and engineering [18, 55].

6 Membrane Technology

6.1 Types of Membranes and Their Mechanisms

Membrane technology is central to treating high-salinity wastewater, with various membrane types offering distinct separation and purification mechanisms. Graphene oxide (GO) membranes, noted for their ultrathin structure and high flux, are particularly effective for desalination in the coal chemical industry due to their energy efficiency and selective ion rejection [56]. The SF theory provides a framework for understanding transport dynamics across these membranes, emphasizing interface interactions crucial for optimizing performance and reducing energy consumption [57].

Membrane design significantly impacts treatment efficacy, with research highlighting the relationship between membrane structure, fouling propensity, and energy requirements [58]. Innovations in materials, such as nanoporous graphene created via argon-plasma magnetron sputtering, enhance filtration properties by promoting selective ion passage through nanoscale pores [59]. Additionally, the Reactive Porous Interface Model (RPIM) simulates fluid flow, solute transport, and chemical reactions at the membrane interface, maintaining functionality and longevity [60].

Advanced designs, such as electrically conductive diamond membranes, enable electrochemical reactions at the membrane surface, showcasing the potential of novel materials to enhance performance [38]. By integrating advanced materials and innovative designs, membrane technology improves the efficiency and sustainability of wastewater management systems, supporting the coal chemical industry's long-term sustainability through effective reclamation and reuse [60, 61, 45, 47, 17].

6.2 Challenges in Membrane Technology

Membrane technology faces several challenges in high-salinity wastewater treatment, notably membrane fouling, which leads to concentration polarization (CP) and increased energy costs [62]. Accurate characterization of the CP layer and mass transfer coefficients is essential for predicting performance under varying conditions [57]. Fouling mechanisms depend on foulant types and operating conditions, with defects from fabrication methods exacerbating issues [58]. GO membranes face challenges in controlling interlayer spacing, limiting ion rejection capabilities [63].

As illustrated in Figure 7, the primary challenges in membrane technology are highlighted, specifically focusing on membrane fouling, stability, and performance optimization. Each aspect is supported by key studies that address these critical issues. Membrane stability and performance in aqueous environments are concerning, with many organic membranes struggling to maintain structural integrity. This highlights the need for robust materials, like all-carbon membranes, which offer enhanced mechanical strength [64]. However, the high cost of advanced materials like diamond membranes may limit their use to high-performance scenarios [60]. Real-world applications necessitate further exploration of physical mechanisms, as varying water qualities and contaminants critically influence performance [65]. Electroconvection-induced deionization shocks offer potential methods for controlling ion transport [29].

Addressing these challenges is crucial for enhancing membrane technology's efficacy and sustainability in high-salinity wastewater treatment, reducing operational costs, and ensuring environmental compliance [17, 47, 45].

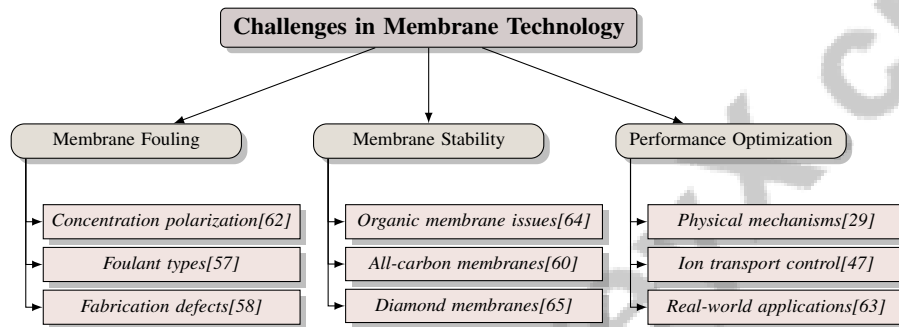


Figure 7: This figure illustrates the primary challenges in membrane technology, focusing on membrane fouling, stability, and performance optimization, with references to key studies addressing each aspect.

6.3 Recent Advancements and Innovations

Recent advancements in membrane technology have significantly improved high-salinity wastewater treatment efficiency and sustainability. All-poly(ionic liquid) membranes allow for controlled pore architecture, achieving high evaporation rates and environmental friendliness [66]. The thermal decomposition of hydrated graphite enhances thermal stability and cleaning capabilities [67], addressing limitations of organic materials.

As illustrated in Figure 8, these advancements in wastewater treatment, particularly focusing on membrane technology, electrokinetic transport, and advanced oxidation processes, highlight key innovations and their implications for sustainability and efficiency. Membrane distillation's scalability and fouling resistance further emphasize its potential for small-scale applications powered by renewable energy [46]. Multiscale models for electrokinetic transport in porous media provide insights into ion transport and separation mechanisms, crucial for optimizing membrane processes [68]. These innovations underscore significant improvements in high-salinity wastewater treatment, promoting sustainability and compliance with environmental regulations. Incorporating natural minerals as cost-effective catalysts in advanced oxidation processes (AOPs) further enhances treatment efficiency, addressing water scarcity and health risks from untreated wastewater [11, 12].

7 Integration of Treatment Methods

7.1 Integration with Other Technologies

Combining advanced oxidation processes (AOPs) with membrane technologies and complementary methods enhances high-salinity wastewater treatment in the coal chemical industry. Integrating reverse osmosis, electrodialysis, and shock electrodialysis mitigates the limitations of individual methods, improving water purification efficiency. This synergy optimizes desalination and filtration while facilitating disinfection and effective brine management, leading to superior treatment outcomes and sustainable water resource management [19, 47, 48, 17, 55].

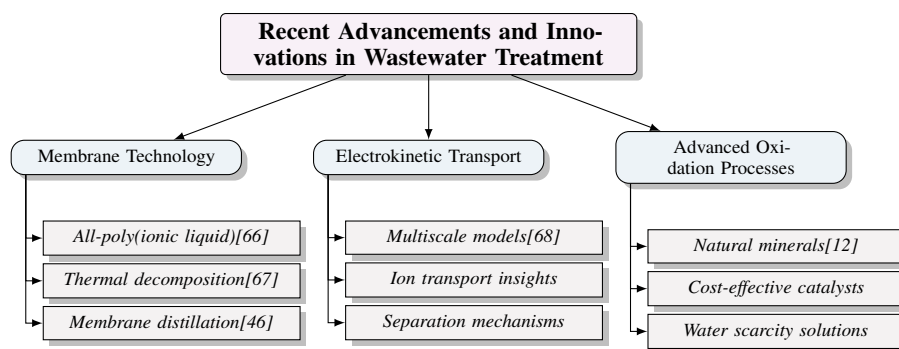


Figure 8: This figure illustrates recent advancements in wastewater treatment, focusing on membrane technology, electrokinetic transport, and advanced oxidation processes, highlighting key innovations and their implications for sustainability and efficiency.

Coupling AOPs with membrane processes concurrently degrades organic pollutants and removes dissolved salts. Sulfate radicals generated in AOPs, activated by peroxymonosulfate (PMS) and persulfate (PS), enhance the breakdown of complex contaminants, reducing downstream fouling potential. This integration improves operational efficiency and extends membrane lifespan, especially when paired with ultrafiltration, making it viable for wastewater and micropollutant treatment [20, 18].

Integrating electrochemical methods with membrane technology further optimizes treatment. Techniques like shock electrodialysis pre-treat high-salinity wastewater, reducing salt concentration and organic load before membrane filtration. This pre-treatment minimizes fouling and scaling, enhancing membrane stability and efficiency, prolonging reverse osmosis membrane lifespan, and improving overall water treatment performance [17, 45].

Incorporating nanofluidic devices into treatment systems enhances ionic transport and separation. The intrinsic interface adsorption properties of nanofluidic channels improve performance predictions and treatment outcomes [69]. These devices, integrated with existing technologies, enhance ion selectivity and reduce energy consumption, contributing to sustainable wastewater management.

Strategically integrating diverse treatment technologies addresses high-salinity wastewater challenges. Leveraging AOPs, membrane technology, and advanced methods, the coal chemical industry can improve wastewater treatment efficiency and sustainability. This integration ensures compliance with environmental regulations, facilitates reclaimed wastewater use, and reduces reliance on limited freshwater resources. Combining AOPs with membrane technology enhances water quality and extends membrane lifespan, addressing increasing water demand and persistent organic pollutants in wastewater [17, 11, 18].

7.2 Multi-Objective Optimization Framework

Managing high-salinity wastewater in the coal chemical industry requires multi-objective optimization frameworks to enhance treatment efficiency, minimize costs, and reduce environmental impact. This is crucial given the challenges of conventional methods, such as harmful byproducts from catalytic ozonation and reliance on advanced technologies like membrane processes and electro-sorption for water reclamation and energy consumption reduction. Integrating approaches like simultaneous mineralization and dehalogenation helps navigate wastewater treatment complexities, ensuring sustainability and regulatory compliance [70, 17, 14, 13]. These frameworks optimize interactions between treatment technologies, ensuring peak performance while minimizing negative externalities.

Applying machine learning algorithms to model and predict integrated treatment system performance is one optimization approach. These algorithms identify optimal operational parameters that enhance AOPs and membrane technologies' synergy, improving treatment outcomes [69]. Reinforcement learning techniques dynamically adjust parameters in response to varying wastewater characteristics, maintaining system adaptability and efficiency [36].

Incorporating life cycle assessment (LCA) methodologies is critical in multi-objective optimization frameworks. LCA evaluates treatment technologies' environmental impacts, identifying trade-offs

between efficacy and sustainability [19]. Integrating LCA with optimization algorithms develops treatment strategies achieving high pollutant removal while minimizing resource consumption and emissions, aligning with sustainable development goals.

Employing multi-scale modeling techniques enhances understanding of transport phenomena within integrated systems. These models simulate interactions between treatment processes at different scales, providing insights into mechanisms driving treatment efficiency and highlighting improvement areas [68]. By capturing ion transport and reaction kinetics dynamics, multi-scale models optimize treatment processes, ensuring effective operation across conditions.

Advancing multi-objective optimization frameworks is crucial for integrating innovative methods, such as AOPs and membrane distillation, into the coal chemical industry. These frameworks enhance decision-making regarding environmental sustainability, economic viability, and resource management amidst stringent regulations and the need for efficient water and energy use [47, 71, 7, 12]. By combining machine learning, life cycle assessment, and multi-scale modeling, these frameworks establish a robust foundation for optimizing treatment systems, ensuring high performance while meeting environmental and economic objectives.

8 Case Studies and Applications

The treatment of high-salinity wastewater has driven the advancement of innovative methodologies, notably electro-sorption processes, which enhance ion removal efficiency while reducing energy use. This section delves into the mechanisms, advancements, and challenges of electro-sorption process simulation, highlighting its implications for sustainable wastewater management.

8.1 Electro-Sorption Process Simulation

Electro-sorption processes, such as capacitive deionization and flow-electrode capacitive deionization, offer effective solutions for high-salinity wastewater treatment through electrostatic adsorption. These methods are ideal for desalination and selective resource extraction but face challenges like solution-switching and mixing effects that affect ion removal efficiency [72, 70, 73, 48, 41]. Performance depends on electrode material properties, system configuration, and operational parameters.

Advancements, such as ambipolar ion pumping ratchets (RBIP), show promise in managing salt flux without moving parts or redox reactions, enhancing system durability [74]. However, optimizing electro-sorption systems remains challenging due to mixing effects, emphasizing the need for a comprehensive understanding of electrode-electrolyte interactions [70].

Combining electro-sorption with advanced treatments like reverse osmosis (RO) can improve outcomes by reducing fouling potential and enhancing system efficiency [45]. As illustrated in Figure 9, the hierarchical structure of electro-sorption process simulation categorizes methods, challenges, and advanced treatment strategies for high-salinity wastewater management. Real-world simulations demonstrate the effectiveness of electro-sorption in addressing high-salinity wastewater challenges. Innovative design and integration strategies can significantly enhance wastewater management's sustainability and efficiency in the coal chemical industry. This approach ensures compliance with environmental standards and facilitates the treatment of refractory organic pollutants using advanced oxidation processes (AOPs) and cutting-edge technologies. Utilizing natural minerals as catalysts further supports pollutant degradation, aiding in the preservation of freshwater resources amid global water scarcity [17, 11, 14, 12].

8.2 Nanofluidic and Electro-Osmotic Applications

Nanofluidic and electro-osmotic processes offer innovative solutions for high-salinity wastewater treatment, enhancing ion separation selectivity and efficiency. Experiments demonstrate that intrinsic molecular interactions in nanofluidic channels lead to significant ionic selectivity and streaming currents, highlighting their potential for high-performance desalination [69].

Incorporating nanofluidic devices into treatment systems improves ionic selectivity and reduces energy consumption, advancing desalination sustainability. These devices exploit nanoscale phenomena, such as enhanced water flow through sub-nanometer pores, allowing superior salt ion filtration compared to traditional membranes. Optimizing nanopores' physical and chemical characteristics enhances water

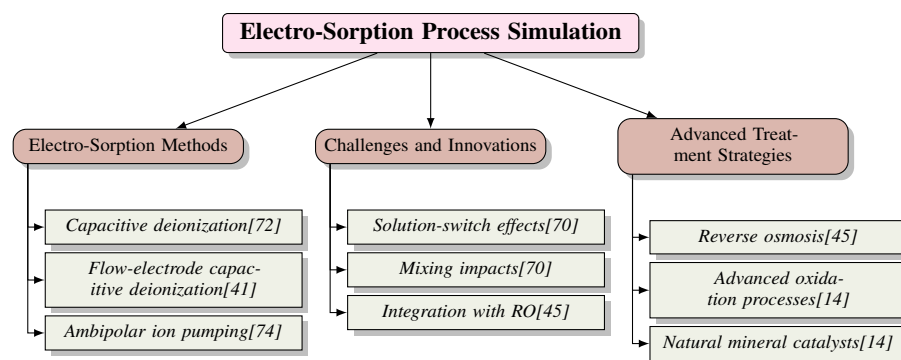


Figure 9: This figure illustrates the hierarchical structure of electro-sorption process simulation, categorizing methods, challenges, and advanced treatment strategies for high-salinity wastewater management.

permeability without compromising salt rejection, leading to effective, energy-efficient desalination [13, 40, 72, 47, 65].

Electro-osmotic processes reduce fouling and scaling in membrane systems. Insights from electro-sorption studies on mixing limitations apply to electro-osmotic applications [70]. Addressing these challenges optimizes electro-osmotic system design and operation, enhancing effectiveness in high-salinity environments.

Innovative applications of nanofluidic and electro-osmotic processes advance high-salinity wastewater treatment. Integrating AOPs and membrane technologies with existing methods enhances wastewater management in the coal chemical industry. This integration facilitates refractory organic pollutant removal, compliance with environmental regulations, and sustainable reuse of treated wastewater. Leveraging natural minerals as catalysts in AOPs optimizes treatment efficiency and reduces costs, supporting long-term wastewater management viability amid increasing water scarcity [12, 14, 11, 17, 18].

8.3 Protocell Technology in Environmental Treatment

Protocell technology presents a novel approach to high-salinity wastewater treatment by mimicking biological systems for enhanced contaminant removal. This technology is promising for the coal chemical industry, where conventional methods struggle with complex wastewater compositions. Integrating advanced membrane technologies and AOPs, known for strong oxidation capacity and minimal secondary pollution, protocell technology improves wastewater treatment and reclamation, addressing the need for sustainable solutions amid global water scarcity [17, 11, 12].

Protocells encapsulate reactive agents within semi-permeable membranes for targeted pollutant interactions, particularly in desalination. Engineered protocells selectively sequester ions and organic pollutants, optimizing removal efficiency [75]. Studies on overlimiting current in microchannels show how protocell technology enhances ion transport and separation, paving the way for treatment advancements.

Protocell technology's adaptability allows for integrating functional components, like catalytic and adsorptive agents, within its structure. This creates multifunctional treatment systems targeting multiple contaminants, enhancing wastewater management's effectiveness and sustainability. These systems leverage cutting-edge technologies, including AOPs and membrane technologies, effective in removing micropollutants and toxic organic compounds, improving reclaimed water quality for industrial, agricultural, and domestic applications [17, 14, 18, 12].

Exploring protocell technology in environmental treatment highlights its potential to transform high-salinity wastewater management in the coal chemical industry. By harnessing protocells' unique characteristics, this technology offers a promising pathway for developing innovative, efficient treatment solutions for wastewater management and desalination. It enhances compliance with environmental regulations and contributes to water resources' long-term sustainability by enabling

wastewater reclamation and reuse across sectors, addressing global water scarcity and pollution challenges [17, 3, 21, 12].

9 Challenges and Future Prospects

9.1 Technical Challenges in Advanced Treatment Methods

Advanced treatment methods for high-salinity wastewater in the coal chemical industry face considerable technical challenges, particularly in scalability, economic feasibility, and operational stability. Scalability issues arise from defects in advanced materials like membranes, which affect selectivity and long-term performance. Additionally, brackish water desalination methods face bottlenecks due to membrane liquid entry pressure limitations [56]. Economic feasibility is hindered by high capital and operational costs, restricting deployment in resource-limited regions [46]. Although capacitive deionization (CID) offers cost advantages, its efficacy is compromised by charge efficiency losses due to non-selective diaphragms [72]. Economic viability also depends on optimizing initial parameter settings, as demonstrated in AHOA applications [1].

Operational challenges, notably membrane fouling, impede progress. Effective fouling mitigation requires customized solutions tailored to specific operational conditions [45]. Variability in these conditions limits the generalizability and practical applicability of existing models [70]. Research continues to address fouling, high operational costs, and the need for specialized membranes [17]. Theoretical gaps further complicate filtration technology advancement, particularly in understanding the quantitative relationship between water permeance and membrane parameters [38]. Proposed methods often overlook real-world factors like membrane fouling and fluctuating salt concentrations, crucial for successful technology implementation [39].

Addressing these challenges is vital for sustainable wastewater management in the coal chemical industry, ensuring regulatory compliance and promoting long-term sustainability through responsible resource management [17, 11, 47, 12].

9.2 Future Research Directions

Future research on high-salinity wastewater treatment in the coal chemical industry should focus on several key areas to overcome existing challenges and improve treatment efficiency. Scaling up synthetic graphene oxide (GO) leaf technology and optimizing its design for enhanced water transport and salt exclusion mechanisms could significantly boost membrane desalination performance [25]. Optimizing fabrication processes for nano-reduced graphene oxide (nano-rGO) membranes and exploring two-dimensional materials are crucial for enhancing ion sieving and ensuring long-term stability [38]. Developing fouling-resistant membranes and hybrid systems that combine different membrane processes is essential for improving energy efficiency and operational sustainability [17].

Further research should examine variable surface charge effects and develop complex models to enhance understanding of ion transport dynamics during desalination shocks [54]. Experimental validations of salt parameterization and alternative ionic models are needed to optimize desalination performance [39]. Investigating electrically conductive diamond membranes in diverse chemical environments and developing cost-effective fabrication techniques could facilitate large-scale applications, given their chemical stability and performance [60].

Focusing on advanced oxidation processes (AOPs) and using natural minerals as heterogeneous catalysts can substantially improve wastewater management in the coal chemical industry. This strategy enhances the removal of refractory organic pollutants, ensuring regulatory compliance and promoting sustainable operations through cost-effective, environmentally friendly treatment methods. Insights into optimizing process factors like catalyst dosage, pH, and temperature will contribute to more efficient and sustainable solutions [11, 12].

9.3 Regulatory and Environmental Considerations

Regulatory frameworks and environmental considerations significantly impact the development and implementation of treatment technologies for high-salinity wastewater in the coal chemical industry. Regulations ensure adherence to stringent environmental standards, minimizing ecological impacts and safeguarding public health. They impose strict limits on permissible contaminant levels

in discharged water, compelling industries to adopt advanced treatment methods like membrane technologies and advanced oxidation processes, which effectively reduce pollutants and facilitate wastewater reuse for agricultural and industrial applications [17, 19, 12].

Environmental considerations are crucial in designing and operating treatment technologies, addressing the adverse effects of high-salinity wastewater on ecosystems and human health. Persistent organic pollutants and heavy metals necessitate treatment methods capable of high contaminant removal rates. Studies indicate that electrode design in electro-sorption processes must consider capacity and mixing effects to optimize performance, highlighting the need for tailored solutions to specific environmental concerns [70].

Future research should focus on automating parameter tuning to enhance treatment efficiency, aligning with efforts to improve processes and ensure adaptability to evolving regulatory standards and environmental conditions [1]. By prioritizing these areas, the coal chemical industry can develop more sustainable and compliant wastewater management practices, aligning with regulatory requirements and sustainability goals.

10 Conclusion

Addressing the complex challenges of high-salinity wastewater in the coal chemical industry necessitates the adoption of advanced treatment methodologies. Graphene-based membranes emerge as highly efficient and environmentally friendly solutions, offering significant potential for future desalination technologies. When integrated with electrochemical advanced oxidation processes, these membranes effectively target and mineralize persistent pollutants, including synthetic dyes, thereby advancing sustainable wastewater management. The implementation of such technologies is crucial for reducing the environmental footprint associated with brine disposal.

Incorporating feedback-driven resource allocation mechanisms further optimizes system performance, surpassing traditional strategies by enhancing the efficiency and adaptability of treatment systems under varying operational demands. Recent studies into the behavior of nanoconfined water offer new perspectives on fluid dynamics, which are pivotal in refining filtration technology designs.

Future research should prioritize optimizing the design and scalability of graphene-based membranes, investigating their potential integration with other innovative treatment technologies, and evaluating the economic feasibility of these advanced methods. Moreover, as the current estimates of brine production are substantially underestimated, developing effective brine management strategies is of paramount importance. Exploring simpler synthetic systems, such as protocells, could also meet specific biotechnological requirements and drive the creation of novel treatment solutions.

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