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Electrodialysis coupled with nano-activated carbon (ED-NAC): a promising technology for the removal of trace pollutants in saline-alkaline waters

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1 Introduction

1.1 Salinization of groundwater seriously affects agricultural production and the ecological environment

With the advancement of economic development and population growth, the problem of groundwater salinization in arid and semi-arid regions globally has become increasingly prominent. Studies showed that the salinization issue was particularly severe in coastal areas in China, where the total dissolved solids content in groundwater exceeded 2,000 mg/L in some regions (Zhao et al., 2022). Groundwater salinization is primarily caused by natural factors such as seawater intrusion and evaporative concentration, as well as anthropogenic factors including overexploitation of groundwater, improper agricultural irrigation, industrial wastewater discharge, and defects in urban drainage systems. These factors lead to the accumulation of salts in the soil and groundwater, exacerbating the salinization process. Groundwater salinization is characterized by a significant increase in salts and alkaline substances. This leads to increased water hardness and reduced usability. It has a negative impact on agricultural irrigation and triggers secondary soil salinization, thereby affecting the living environment of plants, animals, and microorganisms (Yang et al., 2022).

1.2 Long-term accumulation of trace contaminants in saline-alkaline water further exacerbates human health risks

As a result of long-term human activities, groundwater salinization areas are often accompanied by trace contaminants such as antibiotics, pesticides, heavy metals (e.g., arsenic and lead) and fluoride. The long-term accumulation of these pollutants poses a significant threat to human health. The persistence of antibiotics can lead to the spread of antibiotic resistance genes in groundwater and facilitate the dissemination of resistance. The accumulation of drug-resistant pathogens is a direct threat to human health. It also disrupts the microbial balance in ecosystems, which affects the natural purification functions of soil and

TABLE 1 Common saline-alkaline water desalination technologies and their strengths and weaknesses.

Desalination technologies	Principle	Strengths	Weaknesses	References
Electrodialysis	Ions are driven through selective ion-exchange membranes by an electric field	• Relatively low energy consumption • Suitable for low to medium salinity water • Strong resistance to fouling • Easily combined with renewable energy sources	• Low removal efficiency for organic and trace pollutants • Potential for membrane surface fouling	Al-Amshawee et al. (2020) and Patel et al. (2024)
Reverse osmosis	Water molecules are driven through a semipermeable membrane under high pressure	• High salt removal efficiency • Can treat water bodies with various salinities • Effective in removing a variety of pollutants	• High energy consumption • Severe membrane fouling and scaling issues • Requires frequent maintenance	Patel et al. (2022) and Harby et al. (2024)
Activated carbon adsorption	Impurities are adsorbed onto the porous structure and captured within its pores	• Effectively removes organics, chemicals, and odors • Simple operation, suitable for a variety of water treatment applications	• Ineffective for reducing water hardness • Activated carbon requires periodic replacement or regeneration • Subject to interference from competitive ions	Jeirani et al. (2017) and Muhammad et al. (2022)
Distillation	Water is evaporated by heating and then condensed to obtain pure water	• Suitable for high salinity water bodies, high salt removal efficiency • Suitable for use under extreme conditions	• Extremely high energy consumption, high equipment maintenance costs • Not suitable for large-scale application	Kariman et al. (2023) and Shocron et al. (2022)
Capacitive deionization	Salt ions are adsorbed onto electrodes using an electric field	• Low energy consumption • Suitable for low salinity water • Modular system, easy to scale up	• Low efficiency in treating high salinity water • Not suitable for high salinity wastewater	Shocron et al. (2022) and Wang et al. (2024)

water bodies (Chng et al., 2020). Moreover, high concentrations of fluoride, when people are exposed to them for extended periods, pose health risks such as cardiovascular disease and osteoporosis (Kumar et al., 2020). Therefore, the issue of groundwater salinization and its associated trace pollutants urgently requires attention and must be addressed through integrated management measures.

2 Electrodialysis and activated carbon in the spotlight for saline-alkaline water desalination and contaminant remediation

Desalination technologies are a class of treatment methods aimed at removing salts and other contaminants from saline water bodies to obtain fresh water resources. These technologies are widely used in water-scarce areas, especially in coastal arid and semi-arid regions, to meet the needs of drinking water, agricultural water, and industrial water. Common saline-alkaline water desalination technologies and their strengths and weaknesses are shown in Table 1.

2.1 Electrodialysis (ED) technology is an efficient way to desalinate saline-alkaline water

Electrodialysis (ED) is a process that utilizes an electric field to drive the separation of ions through selective membranes, exhibiting high efficiency in desalinating saline-alkaline water. It is particularly effective for treating waters with salinities in the range of 1–10 g/L, significantly reducing the salt content while maintaining a high rate of freshwater recovery (Al-Amshawee et al., 2020). This is of significant importance in alleviating the global freshwater scarcity issue. Compared to other desalination technologies, ED stands out with its resistance to fouling and scaling, compact system size, high flexibility, and particularly lower investment costs for small-scale applications. For instance, ED has reportedly achieved an energy consumption of 1.8 kWh/m^3 in seawater desalination, which is lower than that of reverse osmosis systems (3–4 kWh/m^3) (Patel et al., 2022). Furthermore, ED can be easily integrated with renewable energy systems, offering new possibilities for sustainable freshwater production (Hopsort et al., 2024).

2.2 Nano-activated carbon (NAC): as a green strategy to capture trace pollutants in saline-alkaline water

Mechanically processed nano-activated carbon (NAC) is recognized as an effective strategy for capturing trace pollutants, including pesticides, dyes, and pharmaceutical residues, in saline-alkaline waters, owing to its high adsorption capacity and environmental compatibility. NAC's porous structure endows it with a vast surface area and abundant functional groups, facilitating the efficient adsorption of organic pollutants, heavy metal ions, and other harmful substances from water

(Muhammad et al., 2022). NAC's pollutant remediation primarily involves mechanisms such as physical adsorption, which captures a wide range of pollutants, π-π interactions that target specific organic molecules, hydrogen bond formation for selective adsorption, hydrophobic effects that draw out nonpolar contaminants, and ion exchange for metal ion capture (Jeirani et al., 2017). Furthermore, the regenerable nature of NAC offers long-term economic and environmental advantages in water treatment.

3 ED-NAC coupling process as a low-cost sustainable solution for saline-alkaline water treatment

ED demonstrates numerous advantages in treating saline-alkaline water, yet it faces challenges in concurrently removing trace pollutants found in complex water bodies. NAC, utilizing its vast specific surface area and porous structure, successfully eliminates trace pollutants from water through physical and chemical adsorption. However, in water bodies characterized by high salinity and complex organic matter, the adsorption efficiency of NAC can be hindered by competitive ions and organic compounds. Notably, ED has the capacity to enhance the adsorption efficiency of NAC by removing competitive ions from the water and boosting the electrochemical activity of NAC. For example, Altınbaş et al. (2022) demonstrated that the presence of an adsorbent in an Adsorption-ED hybrid system substantially enhanced the removal rate of boron from actual geothermal saline-alkaline water, increasing it from 7.2% to 73.3%. Furthermore, the combined process of chemical precipitation, bipolar membrane ED, and AC adsorption reported by Ye et al. (2022) successfully eliminated heavy metals (removal efficiency >99%), inorganic salts (>92%), and total organic carbon (>58%), while recovering acids and bases from complex soil-washing wastewater. Additionally, the continuous operation of ED increases the regeneration frequency of NAC, alleviating aggregation issues and thereby reducing operational costs. Patel et al. (2024) reported that ED has better economics and recovery compared to reverse osmosis at feed salinities up to 3 g/L. In addition, It has been noted that nano-activated carbon prepared from agricultural waste is cost-effective, with an economic value of about $3/kg, and can be reused without significant loss of adsorption capacity (Muhammad et al., 2022). Thus, the coupled ED-NAC process not only overcomes the limitations of a single method and significantly improves the treatment efficiency of saline-alkaline water but also mitigates environmental impacts and enhances resource recycling.

4 Broad application prospects of ED-NAC coupling process

In the midst of the heightened consciousness surrounding environmental protection and sustainable resource utilization, the ED-NAC coupling process emerges as a highly efficient and eco-friendly solution for addressing pollutants present in saline-alkaline water. To scale it up from the laboratory to real-world engineering applications, we need to adopt the following strategies: Firstly, a detailed analysis of water quality, tailored to the characteristics of saline-alkaline water from various sources, is essential for selecting appropriate process parameters and treatment strategies. Secondly, to ensure economic feasibility, optimization of energy consumption and reduction in the frequency and cost of NAC replacement are crucial. Thirdly, considering the long-term sustainability of the technology is imperative, which encompasses developing efficient material regeneration methods and rational waste treatment solutions. Lastly, ongoing focus on technological innovation and optimization is vital, including the use of sensors and intelligent control systems for real-time monitoring of water quality and automatic adjustment of process parameters based on data feedback, as well as the integration of machine learning algorithms for analyzing historical and real-time data to optimize parameters and operational strategies, ultimately enhancing the overall system performance and efficiency. These efforts will make a more significant contribution to water resource protection, environmental remediation, and the achievement of sustainable development goals.

Author contributions

XJ: Data curation, Investigation, Writing–original draft. HJ: Data curation, Investigation, Writing–original draft. ZH: Resources, Validation, Writing–original draft. CZ: Conceptualization, Supervision, Validation, Writing–review and editing. HC: Conceptualization, Supervision, Writing–review and editing.

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Conflict of interest

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