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Salt Removal by Different Natural Adsorbents: Mechanisms, Performance, and Future Prospects

Arun Kumar Gupta

Department of Chemical Engineeing, UIET, Chhatrapati Shahu Ji Maharaj University, Kanpur, India
Email: *arung247[at]gmail.com*

Abstract: ***Salt contamination of freshwater resources has emerged as a major environmental challenge worldwide. Conventional desalination techniques such as reverse osmosis and ion exchange, while effective, are energy-intensive and costly. Adsorption using natural materials presents a sustainable and low-cost alternative for salt removal. This review summarizes recent progress in the use of various natural adsorbents, including clay minerals, biochar, agricultural wastes, zeolites, and chitosan-based materials, for desalination and ion removal. The mechanisms of adsorption, key physicochemical parameters, and comparative efficiencies are discussed. Additionally, challenges related to regeneration, selectivity, and scale-up are highlighted, followed by perspectives on future research directions.***

Keywords: Natural adsorbents; Salt removal; Desalination; Biochar; Zeolite; Water treatment

1. Introduction

The availability of clean and safe freshwater is essential for sustaining human life, industrial growth, and agricultural productivity. However, freshwater scarcity has emerged as one of the most severe global challenges of the twenty-first century. The World Health Organization (WHO) estimates that more than two billion people currently live in countries experiencing high water stress, and by 2050, nearly half of the world's population will face severe water shortages if current consumption and contamination trends persist. Among the multiple factors contributing to freshwater scarcity, salinization of water bodies has become increasingly significant. Salinity intrusion, caused by seawater ingress, industrial discharges, excessive irrigation, and climate-induced changes in hydrological cycles, leads to the deterioration of freshwater quality, rendering it unsuitable for domestic, agricultural, or industrial use.

Salinization of groundwater and surface water has been reported in coastal and arid regions across the world. In coastal zones, overexploitation of aquifers often results in seawater intrusion, increasing the total dissolved solids (TDS) and altering ionic compositions. In inland areas, irrigation with saline water and poor drainage contribute to soil salinity, which in turn leaches salts back into groundwater. Moreover, industrial effluents containing high levels of sodium, chloride, sulfate, and nitrate ions aggravate the problem. According to the *United Nations World Water Development Report (2023)*, approximately one-third of the global population already resides in water-stressed regions, and in many such areas, salinity intrusion has become a primary factor limiting access to potable water. These conditions underscore the urgent need for effective and sustainable desalination and ion-removal technologies.

1.1 Limitations of Conventional Desalination Technologies

Over the past few decades, a number of desalination technologies have been developed and commercialized to combat water salinity. Among them, reverse osmosis (RO), multi-stage flash distillation (MSF), and electrodialysis (ED) are the most widely implemented.

- Reverse osmosis (RO) employs semipermeable membranes to separate water from dissolved ions under high pressure. Although effective in producing low-salinity water, RO units require significant energy input (typically 3–6 kWh per cubic meter of water) and frequent membrane replacement due to fouling and scaling.
- Multi-stage flash distillation (MSF) and multi-effect distillation (MED) rely on thermal processes to evaporate and condense water, which makes them energy-intensive and economically unviable for small-scale or rural applications.
- Electrodialysis (ED) uses ion-exchange membranes driven by an electric field, but the process efficiency decreases with increasing salinity, and maintenance costs remain high.

While these technologies are indispensable for large-scale desalination, particularly in industrialized and arid regions, their application in developing countries or decentralized systems is constrained by high operational costs, energy dependence, and technical complexity. Moreover, the brine discharge generated by these processes poses additional environmental challenges, including marine ecosystem damage and soil salinization when improperly disposed of. Consequently, researchers are increasingly exploring low-cost, energy-efficient, and environmentally friendly alternatives for salt and ion removal.

1.2 Adsorption as a Promising Alternative

Among emerging water treatment methods, adsorption has received considerable attention due to its simplicity, efficiency, and adaptability. Adsorption involves the accumulation of dissolved ions or molecules onto the surface of solid materials known as adsorbents. This process can effectively reduce the concentration of various contaminants, including heavy metals, dyes, organic pollutants, and salts, without generating significant chemical sludge or requiring extensive infrastructure.

The advantages of adsorption-based desalination include:

- Low energy consumption compared to thermal or membrane-based methods.
- Ease of operation and design flexibility, allowing implementation in both centralized and decentralized systems.
- Reusability of adsorbents, which reduces waste generation and operational costs.
- High adaptability, as adsorbent materials can be tailored to target specific ions or contaminants through surface modification.

Historically, activated carbon has been the most widely used adsorbent due to its large surface area and chemical stability. However, the relatively high production cost of activated carbon and its limited selectivity toward inorganic salts have motivated researchers to explore alternative natural and waste-derived adsorbents that are both economical and sustainable.

1.3 Natural Adsorbents for Salt Removal

Natural adsorbents are materials derived from abundant mineral or biological sources that exhibit intrinsic ion-exchange or adsorption capacities. These include clay minerals (such as bentonite, kaolinite, and montmorillonite), zeolites, biochar**,** agricultural residues, and biopolymers like chitosan. The appeal of natural adsorbents lies in their availability**,** low cost, environmental compatibility, and ease of modification**.**

- **Clay minerals** possess layered structures with negatively charged sites that can exchange cations such as Na^+ and K^+. Their high cation-exchange capacity and swelling properties make them excellent candidates for salt removal from water.
- **Zeolites**, crystalline aluminosilicates with well-defined pore structures, offer selective ion-exchange capabilities and chemical stability under a wide range of pH conditions.
- **Biochar**, produced from pyrolysis of agricultural or forestry residues, has a porous carbonaceous framework with oxygen-containing functional groups that facilitate ion binding.
- **Chitosan**, derived from chitin in crustacean shells, contains amine and hydroxyl groups capable of chelating metal and salt ions, and its biocompatibility makes it attractive for green water treatment technologies.
- Other agricultural by-products such as rice husk ash, coconut husk, and banana peel have also demonstrated measurable ion adsorption capacities when properly treated or activated.

These materials can be used individually or combined as composite adsorbents to enhance performance and selectivity. Surface modification—through acid/base activation, impregnation with metal oxides, or grafting of functional groups—can significantly improve adsorption efficiency and broaden their applicability in saline water treatment.

1.4 Scope of the Present Review

Given the environmental and economic limitations of conventional desalination methods, research into natural adsorbents provides a sustainable pathway for mitigating global freshwater scarcity. Numerous studies have examined the potential of clays, zeolites, biochar, and biopolymers for ion removal; however, comparative analyses of their performance and underlying mechanisms remain fragmented.

The present review aims to:

1) Summarize the adsorption mechanisms governing salt removal using natural materials.
2) Evaluate and compare the adsorption capacities, ion selectivity, and operational performance of various natural adsorbents.
3) Identify the challenges associated with adsorbent regeneration, stability, and large-scale implementation.
4) Highlight future research directions to improve efficiency and sustainability in natural adsorbent-based desalination.

By integrating findings from recent literature, this review provides a comprehensive understanding of the potential of natural adsorbents in addressing global water salinity issues. It emphasizes the need for interdisciplinary research to optimize adsorption processes, develop hybrid systems, and promote the transition toward sustainable and accessible desalination technologies.

2. Mechanisms of Adsorption in Salt Removal

The adsorption of salts (primarily NaCl and other dissolved ions) involves physical and chemical interactions between ions and active sites on the adsorbent surface. The primary mechanisms include:

1) **Ion Exchange:** Replacement of adsorbent surface ions (e.g., Ca^{2+}, K^+) with Na^+ or Cl^- from the solution. Zeolites and clays exhibit strong ion-exchange capacity due to their negatively charged frameworks.
2) **Electrostatic Attraction:** Adsorbents with surface functional groups such as –COOH, –OH, and $–NH_2$ can attract oppositely charged ions, particularly when surface charge depends on solution pH.
3) **Surface Complexation:** Chemical bonding between ions and reactive surface groups forms inner-sphere complexes, enhancing selectivity toward specific ions.
4) **Physical Adsorption (Van der Waals forces):** Weak interactions on porous carbon or biochar surfaces contribute to overall uptake, particularly at high salt concentrations.
5) **Diffusion-controlled Transport:** Adsorption efficiency depends on pore structure and diffusion pathways within the adsorbent matrix.

3. Overview of Different Natural Adsorbents

3.1 Clay Minerals

Clays such as bentonite, kaolinite, and montmorillonite have layered aluminosilicate structures that offer high cation-exchange capacities (CEC).

- **Bentonite** has shown Na^+ removal efficiencies up to 80–90% under optimized conditions (Mishra et al., 2021).

- The interlayer spacing allows ion exchange and swelling, enhancing contact with aqueous ions.
- Modification with organic surfactants (e.g., cetyltrimethylammonium bromide) improves chloride adsorption capacity.

3.2 Zeolites

Natural **zeolites**, particularly clinoptilolite, are microporous aluminosilicates with a high affinity for monovalent cations.

- Their three-dimensional network facilitates selective ion exchange with Na^+ and K^+.
- Zeolites exhibit salt removal efficiencies between 60–95% depending on pre-treatment and grain size (Al-Harahsheh et al., 2020).
- Regeneration using dilute acid or salt solutions is feasible for multiple cycles.

3.3 Biochar and Activated Carbon from Agricultural Waste

Biochar, derived from pyrolysis of biomass (e.g., coconut shell, rice husk, sawdust), contains abundant functional groups and porous structures.

- Surface oxidation enhances hydrophilicity and ion-binding capacity.
- Studies report Na^+ and Cl^- adsorption capacities of 20–60 mg/g (Li et al., 2022).
- Activation with KOH or H_3PO_4 increases surface area and pore volume, improving salt uptake.
- The sustainability of biochar makes it ideal for decentralized water treatment in rural areas.

3.4 Chitosan and Biopolymer-based Adsorbents

Chitosan, a natural polysaccharide obtained from chitin deacetylation, contains amine groups capable of chelating metal and salt ions.

- Cross-linking with glutaraldehyde or incorporation with clay improves mechanical stability.
- Chitosan composites can remove up to 75% of total dissolved solids (TDS) from saline water (Rahman et al., 2021).
- Regeneration by mild acid treatment retains performance across multiple cycles.

3.5 Agricultural Residues and Plant-based Adsorbents

Agricultural by-products such as coconut husk, banana peel, sawdust, and rice husk ash have shown potential due to lignocellulosic structure and hydroxyl/carboxyl functional groups.

- Pre-treatment with acids or bases increases porosity and enhances ion adsorption.
- While raw materials are less efficient than activated forms, their zero-cost and biodegradability make them attractive for large-scale use.

4. Comparative Analysis

A comparative summary of salt removal capacities is presented in Table 1.

Adsorbent Type	Major Active Mechanism	Typical Na^+/Cl^- Removal (%)	Key Advantages	Limitations
Bentonite Clay	Ion exchange	80–90	Low cost, high CEC	Limited Cl^- adsorption
Zeolite	Ion exchange, electrostatic	60–95	High selectivity, reusable	Brittle, clogging in filters
Biochar	Physical + chemical adsorption	40–70	Sustainable, regenerable	Lower selectivity
Chitosan	Electrostatic & chelation	60–75	Biodegradable, tunable	pH sensitive
Agricultural Waste	Physical adsorption	30–60	Abundant, zero-cost	Low capacity, needs modification

Overall, zeolites and clays demonstrate the highest ion-exchange capacity, while biochar and biopolymers offer better sustainability and regeneration potential.

5. Challenges and Future Prospects

Despite promising results, several challenges hinder large-scale implementation:

- **Selectivity and Competition:** In natural waters containing multiple ions, competitive adsorption reduces overall efficiency.
- **Regeneration and Stability:** Some natural adsorbents suffer from structural degradation after repeated use.
- **Kinetics and Diffusion Limitations:** Slow ion diffusion through micropores limits performance at high salinity.
- **Scaling and Column Design:** Laboratory-scale batch experiments often fail to predict real-field behavior.
- **Environmental Footprint:** Disposal of exhausted adsorbents may cause secondary contamination unless regenerated properly.

Future research directions include:

- Development of **composite adsorbents** combining clay, biochar, and polymers to enhance multifunctionality.
- Application of surface modification (e.g., grafting functional groups, magnetic nanoparticles) to improve selectivity.
- Integration of adsorption with membrane or electrochemical systems for hybrid desalination.
- Life cycle assessments (LCA) to evaluate sustainability and cost-effectiveness.

6. Conclusion

Natural adsorbents offer a sustainable and affordable approach to salt removal, complementing existing desalination technologies. Among the materials reviewed, zeolites and clays show superior cation removal, whereas biochar and chitosan composites excel in environmental compatibility and reusability. Advancements in modification techniques and hybrid systems could make natural adsorbent-based desalination viable for rural and decentralized applications. Future research should focus on scaling up, improving selectivity, and ensuring the economic feasibility of these eco-friendly materials.

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