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Brine Water Management of Reverse Osmosis

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Among various desalination methods, reverse osmosis (RO) has emerged as the most widely adopted technology due to its efficiency and the availability of advanced polymeric membranes [1]. This method not only produces potable water but is also increasingly utilized in tertiary wastewater treatment.

Despite major advancements aimed to improve productivity and efficiency, RO processes remain energy-intensive, particularly when extracting freshwater from brackish and seawater resources. The specific energy consumption associated with seawater RO (SWRO) typically falls within the range of 2.0 to 3.5 kWh/m³, with an average value of approximately 3.0 kWh/m³ based on the volume of water produced [2]. This considerable energy requirement is largely due to the pumps necessary for overcoming the high osmotic pressure present in the feed solutions. Furthermore, the pursuit of higher potable water recovery results in increasingly concentrated retentate from SWRO, complicating both recovery rates and disposal methods [3].

The discharge from RO systems typically contains a higher concentration of salts, organic compounds, and other contaminants that are present in feedwater [4, 5]. The ratio of the purified water produced (permeate) to discharge of the water (concentrate, retentate or brine) varies based on the salinity and ionic composition of feed water, design of the systems and operating conditions, often ranging from 35 to 90% [6,7].

High salinity levels in the discharge can harm aquatic ecosystems if released into natural bodies of water, leading to osmotic stress for marine life and disrupting habitats [8, 9]. Common disposal methods include dilution in larger bodies of water, deep well injection, or evaporation ponds, each with its own environmental implications and regulatory requirements [10]. The cost of brine disposal is another important issue. Another significant consideration is the cost of brine disposal. In coastal desalination facilities, brine disposal costs can account for 5% to 33% of the total desalination expenses. Inland desalination plants face even higher disposal costs due to the specific characteristics of the brine and the associated treatment requirements [11, 12].

To mitigate the impacts of RO discharge, several technological advances are being explored. Zero Liquid Discharge (ZLD) is one proposed solution for brine management in inland desalination plants, aiming to eliminate any liquid

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waste by recovering and reusing all water while solidifying all dissolved material. ZLD processes recover all water in wastewater streams, leaving only solid waste, which can be disposed of more safely and environmentally friendly [13, 14]. Improved membrane technologies are also being developed to enhance efficiency and reduce the volume of concentrate generated. Minimal Liquid Discharge (MLD) processes, which focus on achieving water recovery rates of approximately 95%, have been proposed as cost-effective alternatives to ZLD, as they require less energy and capital investment [15, 16].

In MLD systems, filtration processes are utilized instead of thermally driven phase-change methods, resulting in a notable reduction in energy consumption compared to ZLD systems, which typically involve multiple stages including pretreatment, preconcentration, evaporation, and crystallization [17, 18]. Integrated systems that combine RO with other treatment processes, such as nanofiltration or ion exchange, can also reduce the concentration of harmful substances in the discharge [19].

Moreover, innovative approaches, such as osmotically assisted RO (OARO) and cascading osmotically mediated RO (COMRO), have been proposed to reduce hydraulic pressure requirements in MLD. However, the practical challenges of constructing bilateral countercurrent modules that operate under conventional RO pressures pose limitations to the widespread implementation of these technologies [13, 20]. Therefore, the advancement of novel technologies capable of concentrating wastewater to high salinities while maintaining moderate pressure and energy requirements is crucial for enhancing the efficiency of both MLD and ZLD processes [21].

In MLD systems, various desalination techniques are integrated into a unified hybrid framework, similar to ZLD systems. However, the exclusive use of membrane-based technologies within MLD systems presents notable advantages. This approach significantly reduces energy and cost requirements, primarily due to the predominance of membrane technologies in MLD treatment schemes, in contrast to ZLD systems, utilizing both membrane and thermal technologies [22]. The MLD framework aligns with the circular economy model—a contemporary sustainable development paradigm that has garnered support from the European Union. Both MLD and ZLD systems contribute to the transition toward a circular economy by minimizing waste generation, reducing carbon dioxide emissions, and optimizing resource utilization[16, 23].

Although RO remains a vital technology for addressing freshwater scarcity, the environmental implications of brine disposal and the high energy demands of the process must be carefully considered. Sustainable management practices and technological innovations are essential to minimize the ecological footprint of desalination processes and protect marine life from the adverse effects of concentrated saline discharges.

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