

Sustainable potable reuse with an integrated forward osmosis-reverse osmosis-electrooxidation system

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Highlights:

- The integration of EO with a hybrid FO-RO facilitates sustainable potable water reuse.
- A critical challenge within the system—nitrogen compound accumulation—can be mitigated by controlling EO operating parameters.
- The integrated system maintains appropriate chloramine levels for subsequent treatment processes.

Keywords: Forward osmosis; reverse osmosis; electrooxidation

INTRODUCTION

Climate change, urbanization, and agricultural activities exert significant pressures on pristine water resources. A recent global assessment projects that by 2050, approximately 80% of the global population may potentially face quantitative and qualitative water scarcity (Wang et al., 2024). In response, potable water reuse has emerged as a critical solution for addressing water scarcity, aligning with the sustainable development goals launched by the United Nations. However, conventional add-on approaches for potable reuse (e.g., the full advanced treatment train) incur high costs due to multiple rounds of chemical dosing and the management of reverse osmosis (RO) brine. Herein, we propose a sustainable approach for producing potable water using a closed-loop hybrid forward osmosis (FO)-RO system (HFR), incorporating an electrooxidation (EO) unit within the draw solution loop between the FO and RO units. The draw solution (e.g., NaCl), used between FO and RO, is enriched and recycled by RO after dilution with permeate water from FO for subsequent rounds of operation as a closed loop, thus reducing the need for RO brine treatment. The EO unit, installed within the draw solution loop, converts

ammonia (traditionally considered a contaminant in wastewater) into valuable chloramine by electrochlorination, thereby further eliminating the need for additional chemical dosing for membrane fouling control, subsequent UV-based advanced oxidation process (AOP), and secondary disinfection. This proof-of-concept study aims to address a critical challenge of this integration—nitrogen compound accumulation in the draw solution—to ensure appropriate chloramine residuals for post-treatment processes (e.g., AOPs) and water supply networks.

METHODOLOGY

The FO module consists of a customized FO cell equipped with a flat-sheet thin film composite (TFC)-polyamide FO membrane (FOMEM-121503, Porifera, USA) separating the feed solution chamber and the draw solution chamber. The feed solution and the draw solution are recirculated from their respective tanks to the FO chambers using two peristaltic pumps. The RO module comprises a cross-flow filtration unit equipped with a flat-sheet TFC polyamide RO membrane (Seamaxx, FilmTec™, USA). A back-pressure regulator and a high-pressure pump are utilized to control the hydraulic pressure and cross-flow velocity. Water flux is monitored using a weighing balance (FX-3000GD, A&D, Japan). The EO unit consists of an Ir-Ru/Ti anode with a geometric working area of 25 cm² and a stainless steel piece serving as the cathode.

RESULTS AND CONCLUSIONS

To evaluate the efficacy of the HFR-EO system in maintaining zero nitrogen accumulation within the closed-loop FO-RO while ensuring appropriate chloramine levels in RO permeate for the subsequent UV/chloramine AOP and secondary disinfection, a detailed calculation framework was developed. This framework tracks nitrogen dynamics, which describe the conversion between different species of nitrogen, and considers the behavior of various nitrogen species (e.g., ammonia nitrogen (NH₃-N), monochloramine (NH₂Cl), and dichloramine (NHCl₂)), across several stages: (1) FO rejection, (2) RO rejection, (3) EO conversion, (4) UV/chloramine conversion, and (5) conversion within distribution networks. The dynamics were analyzed based on experimental and modeling results, as well as data reported in the literature.

The rejection rate of ammonia by FO is estimated to be 50%, and the rejection rates of ammonia, NH₂Cl, and NHCl₂ by RO are assumed to be 93%, 35%, and 15%, respectively, based on experimental results and literature values (Bellona et al., 2008; Lee et al., 2020; Choi et al., 2024). It should be noted that the transformation of nitrogen species during the EO process in the draw solution of FO is complex due to the high salinity nature and the interactions between ammonia and chlor(am)ine species. Based on our preliminary results, an ammonia-free stage can be achieved while maintaining relatively stable chloramine concentrations during EO operation through careful control of the current density, voltage, and hydraulic retention time. During the EO process, 40% of the ammonia is converted to chloramines, and the residual ammonia (60%) is converted to nitrogen-containing gases. After 5 days of operation (Table 1), the concentrations

of chloramines in the RO permeate are still appropriate for the UV/chloramine process. Moreover, the ammonia and chloramine concentrations, after considering the phototransformation during the UV/chloramine process and self-decomposition during a 24-hr distribution, are lower than the drinking water thresholds for chloramine (4 mgCl₂/L) and ammonia (0.5 mgN/L). This finding suggests that integrating the EO process with the FO-RO system is a viable approach for sustainable potable reuse applications. Further laboratory investigations are required to verify the assumptions made in this study and elucidate the chemistry of chlor(am)ines and ammonia in the EO process.

Table 1. Concentrations of ammonia and chloramines after 5 days of system operation.

Parameter	FO feed	RO feed	RO permeate	RO brine	After EO
Flow rate (L/day)	2.00	2.00	1.00	1.00	1.00
NH ₄ ⁺ (mgN/L)	30.00	7.50	0.53	14.48	0.00
NH ₂ Cl (mgN/L)	0.00	2.16	1.40	2.91	4.35
NHCl ₂ (mgN/L)	0.00	2.02	1.72	2.32	4.06

ACKNOWLEDGMENTS

This work was supported by the Hong Kong Research Grants Council (T21-604/19R), the Fundamental Research Funds for the Central Universities (310400209521), and the Talent Startup Fund of Beijing Normal University (310432104 and 312200502503).

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