

Summary

Water scarcity represents one of the most critical global challenges of the 21st century, further exacerbated by significant climatic, demographic, and socio-economic changes that are altering water availability. In this context, conventional water supply schemes, largely relying on surface and groundwater harvesting, face limitations in providing a reliable water supply. To address the increasing mismatch between water demand and availability, it is essential to undertake a paradigm shift from linear management schemes toward a circular water economy, promoting resource recovery and water reuse practices from non-conventional water sources, including industrial wastewater. However, harnessing such sources is often limited by their compositional heterogeneity and complexity, as well as the variability of quality requirements for the intended reuse, which render conventional treatment processes inadequate, thus requiring innovative advanced water treatment technologies and strategies. Among these, membrane-based processes emerge as alternatives for the treatment of complex waste streams, while Zero Liquid Discharge (ZLD) strategies are increasingly explored to address residual waste management. Yet, widespread adoption often requires overcoming not only technical challenges but also non-technical barriers, including socio-economic and regulatory constraints.

Framed around real industrial waste streams, this thesis evaluates advanced treatment strategies, addressing both opportunities and practical challenges

associated with their management, and ultimately aiming to identify tangible valorization pathways for resource recovery and water reuse.

The dissertation is structured into two main thematic chapters presenting four case studies. A common methodological framework is applied, defining fit-for-purpose strategies based on the specific composition of the waste streams and associated operational and regulatory constraints. Chapter 2 assesses resource recovery through thermally driven membrane processes, highlighting the need to align operating conditions with target species equilibria and matrix-specific constraints. In the first study, Osmotic Membrane Distillation (OMD) allowed for the recovery of high-value compounds from agri-food waste streams, while maintaining their bioactivity. For thermolabile compounds, such as phycocyanin, low temperatures (≤ 35 °C) and non-cross-flow configurations were required, revealing a trade-off between product stability and process productivity. The second study proposed and evaluated a multi-step Membrane Distillation (MD) approach for water reclamation and multi-nutrient recovery from aquaculture wastewater. While validated on synthetic solutions, real streams revealed strong matrix interferences affecting struvite recovery and requiring the integration of pretreatments. Nonetheless, the strategy recovered 55–65 % of the initial volume as clean water and 10–15 % as ammonium citrate containing ~90 % of the initial nitrogen.

Chapter 3 examines water reuse applications, highlighting the need to adapt treatment strategies to the intended application. The third case study assesses direct reuse of by-product water from fuel cells for agricultural irrigation, demonstrating

that its low ionic strength causes osmotic imbalances and nutrient depletion (10–15% TOC decrease), thereby requiring adaptive strategies such as mineral supplementation. The last study investigates the remediation of contaminated groundwater, revealing that while single-unit processes cannot fully remove persistent pollutants, their combination in a multibarrier treatment train targeting near-ZLD can produce high-quality water suitable for indirect potable reuse.

Overall, the dissertation contributes to advancing toward a circular water economy by providing generalizable insights and a methodological framework applicable to the treatment of other complex waste streams and the design of resource recovery and water reuse strategies.