MEMBRANE TECHNOLOGY AND WATER RECOVERY

Energy-Efficient Reverse Osmosis and Membrane Technologies for Industrial Water Recovery and Reuse in Saudi Arabia

Soji Jacob

Published November 2026

Abstract

Industrial water recovery is increasingly important in Saudi Arabia, where manufacturing expansion, freshwater scarcity and changing discharge obligations converge. Reverse osmosis offers reliable dissolved-solute removal, but its application to variable industrial effluents is constrained by osmotic pressure, membrane fouling, concentrate disposal and operational energy demand. This critical narrative review examines peer-reviewed research published between 2020 and 2025 on pressure-driven membranes, staged pretreatment, hydraulic energy recovery, high-recovery configurations and hybrid resource recovery. Unlike studies centred on seawater desalination alone, the analysis distinguishes process-water reuse from conventional potable-water production and evaluates technology choices against feed chemistry and intended end use. Evidence indicates that lowering specific energy consumption requires coordinated management of feed variability, operating recovery, membrane flux, pump performance and cleaning frequency rather than a single equipment upgrade. A Saudi-oriented framework is proposed that begins with wastewater segregation and fit-for-purpose specifications, proceeds through risk-based membrane selection, and evaluates residual brine, carbon intensity and operational resilience. The synthesis identifies persistent evidence gaps in full-scale industrial datasets, lifecycle accounting and locally validated hybrid designs. These findings support staged, measurable deployment rather than universal performance claims.

Keywords: Reverse osmosis; industrial wastewater; water reuse; energy recovery; membrane fouling; nanofiltration; Saudi Arabia; concentrate management

1 Introduction

Industrial growth intensifies competition for reliable water while simultaneously creating recoverable effluent streams. In Saudi Arabia, refinery and petrochemical complexes, food processors, power facilities, mineral operations and advanced manufacturing plants impose markedly different demands on water treatment. Their effluents can contain salts, emulsified hydrocarbons, silica, metals, biodegradable organics or treatment chemicals in combinations that fluctuate with production. Conventional supply planning treats incoming freshwater and discharged wastewater as separate problems. Recovery-oriented planning instead regards both as interconnected material flows, with process suitability and water security assessed at the facility boundary. Global desalination analysis establishes the increasing industrial relevance of membrane treatment, but does not itself determine the best design for reclaimed industrial wastewater [1].

Reverse osmosis (RO) separates water from dissolved constituents using a semipermeable barrier and pressure greater than the opposing osmotic difference. Its mature modular design and strong rejection make it valuable for producing utility water, cooling make-up and, with additional controls, high-purity process water. Yet energy demand rises as feed salinity or the required concentration

factor increases. A high nominal rejection rate is insufficient if a membrane train suffers recurring shutdowns, excessive pretreatment losses or expensive residual disposal. The shift from freshwater production to reliable water reuse therefore requires an integrated treatment-train perspective [2,3].

Saudi applications present a particularly demanding combination of high temperatures, variable source-water salinity and geographically concentrated industrial water demands. An industrial site may have access to treated municipal effluent, internally segregated rinses, cooling blowdown or high-strength wastewater; none should automatically be regarded as interchangeable. Water that meets a cooling specification may fail a boiler or electronics manufacturing requirement. Conversely, treating every stream to the highest possible purity can waste electricity, chemical reagents and capital. The environmental burden of concentrate discharge further complicates claims that recovery is unconditionally sustainable [4].

The aim of this review is to formulate an energy-aware decision framework for membrane-enabled industrial reuse in Saudi Arabia. Four objectives guide the synthesis: distinguish feed-dependent membrane duties; evaluate process-level approaches to reducing electricity and fouling; assess high-recovery and concentrate pathways; and translate research insights into auditable industrial implementation criteria. Its contribution is a comparative interpretation of recent evidence rather than new experimental data, an assumed national baseline or a simulated Saudi facility.

Evidence was judged according to the credibility of its design rather than a journal ranking alone. Laboratory membrane comparisons establish selectivity under controlled chemistry but say little about industrial uptime. Pilot trials provide richer hydraulic information, although their feed mixtures and operating periods may be unusually favourable. Reviews support mechanism identification while sometimes aggregating incompatible energy boundaries. Consequently, the evidence is strongest when multiple study types point toward the same operational constraint. Transfer to Saudi facilities is identified as engineering interpretation unless the cited investigation explicitly reports Saudi wastewater. The framework is intentionally qualitative: assigning numerical weights to reliability, energy and water security without plant data would imply precision that the literature cannot support.

2 Review methodology and evidence boundaries

A structured critical narrative review was adopted because the literature spans experiments, pilot plants, process simulations, techno-economic studies and cross-sector reviews whose outcomes cannot be pooled meaningfully into one effect size. The scope was restricted to publications dated 2020–2025 and centred on membrane separation, energy optimisation, industrial reuse, membrane fouling, wastewater pretreatment, concentrate management or the water-energy nexus. Search concepts combined “reverse osmosis”, “industrial wastewater”, “water reuse”, “specific energy consumption”, “energy recovery device”, “nanofiltration”, “membrane bioreactor”, “fouling” and “zero liquid discharge”. Relevant studies were located through scholarly publisher pages, bibliographic repositories and reference tracing, with DOI-linked records checked against source metadata.

Priority was given to articles that disclosed operating configurations, mechanisms, limitations or practical comparisons. Municipal reuse studies were retained when they elucidated transferable fouling and contaminant-removal behaviour; seawater studies were retained only to clarify hydraulic design or the limitations of translating energy benchmarks. Studies restricted to drinking-water attitudes were used solely for contextual governance considerations. Publications dated outside the

specified period were excluded from the numbered bibliography, including the supplied technical example, which informed the choice of engineering questions but not the cited evidence base.

Because this synthesis did not use an archived database export or independently reproduced exhaustive search results, it does not claim systematic completeness, screening counts or a quantitative meta-analysis. Each selected paper was interpreted under five themes: feed characteristics, membrane and pretreatment function, electrical and thermal energy, concentrate outcomes, and operational transferability. Reported numerical results are treated as configuration-specific, never national averages. The principal quality test is whether a finding states enough boundary conditions to inform an industrial decision. This method supports transparent, defensible synthesis without inventing plant datasets or formal evidence statistics.

A useful energy accounting identity separates high-pressure pumping from pretreatment, circulation, cleaning and downstream distribution. Such accounting should retain standby power, particularly where trains operate intermittently. Recovery must also be distinguished from membrane permeability: raising pressure can increase flux immediately but may intensify concentration polarisation and accelerate deposits, reducing lifetime energy efficiency. Pressure setpoints should therefore reflect normalised long-term performance rather than the highest first-day yield. When comparing membranes, equalising feed temperature, salinity, applied recovery and final quality is essential. Exergy-based studies highlight how pumps and flow restrictions contribute losses that cannot be inferred from membrane rejection alone [5]. These considerations explain why minimum energy per cubic metre at the membrane boundary can differ from minimum operating cost per compliant cubic metre at the site boundary.

3 Thermodynamic and operational determinants of energy demand

The minimum separation work is governed by feed composition, product quality and recovery, whereas actual electrical consumption adds irreversibilities in pumping, crossflow, friction, mixing and auxiliary treatment. For saline water, osmotic pressure rises as the remaining concentrate becomes more concentrated. Increasing recovery can therefore save intake and discharge volumes while increasing pressure requirements and scaling propensity. Park and colleagues identified reduced hydraulic irreversibility, effective salinity management and energy recovery as distinct levers rather than interchangeable solutions [2]. The resulting design question is not simply how to maximise recovery, but where additional permeate becomes disproportionately energy-intensive.

Specific energy consumption (SEC), conventionally expressed as kilowatt-hours per cubic metre of useful product, must be measured over a clearly stated process boundary. Pump-only SEC excludes electricity required by equalisation, filtration, aeration, cleaning, disinfection and final transfer. These loads matter particularly when reuse involves highly organic effluent rather than clarified seawater. Alanezi and colleagues demonstrated that recovery optimisation changes once pretreatment energy and energy-recovery-device efficiency are considered [3]. For industrial reuse, SEC should additionally distinguish gross membrane permeate from water actually meeting its application specification; otherwise a plant with substantial rejected or reprocessed product appears artificially efficient.

Energy recovery devices (ERDs) transfer pressure remaining in concentrate back to incoming feed. Their established value for high-pressure seawater trains is supported by reviews of turbine and isobaric configurations and by experiments with integrated pressure-boost systems [6,7]. However, an isobaric exchanger offers limited savings when concentrate leaves a low-pressure brackish-water RO train with little recoverable hydraulic energy. The right comparison accounts for installation

pressure, operational range, mixing, maintenance and minimum stable throughput. Wang and colleagues further emphasised whole-system assessment rather than device efficiency alone [8]. Consequently, ERD procurement should follow a site-specific hydraulic balance instead of copying a seawater design.

Variable operating conditions create an additional penalty. Seasonal temperature shifts affect viscosity and membrane permeability, while intermittent production changes available flow, recovery and pump efficiency. Pilot-plant evidence shows that models can help predict permeate production and conductivity under variable operation, but optimisation depends on the tested membrane and energy-recovery arrangement [9]. Variable-speed drives, pressure monitoring and feedback control can keep a train near its qualified envelope. They do not remove the requirement for adequate crossflow or pretreatment. A realistic control hierarchy first protects product quality and membrane integrity, then minimises electricity subject to production and discharge constraints.

An additional selection issue is the chemistry of trace constituents. Silica can impose recovery limits even when conventional calcium-scaling indices appear acceptable; boron and small uncharged molecules may require special membrane arrangements depending on pH and use. Metals may change oxidation state during pretreatment, altering their separability and deposition risk. High organic concentrations can impair cartridge filters, while microbiologically active streams may regrow downstream of nominal sterilisation. Each challenge requires a chain of evidence: representative sampling, bench screening, compatibility confirmation and pilot observation. A balanced pilot should measure both rejection and the propensity for irreversible fouling. A pressure-driven train is not adequate merely because it reaches target conductivity if its output retains an unacceptable site-specific constituent.

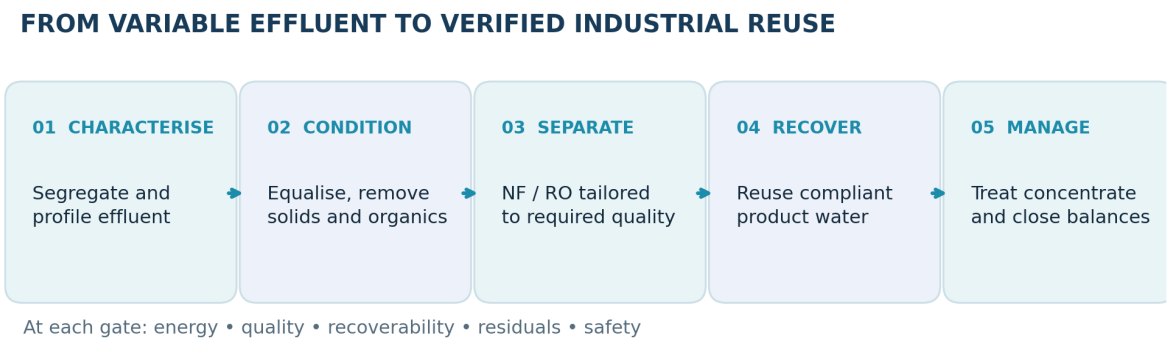

Figure 1. Decision pathway from variable industrial effluent to compliant reuse and controlled concentrate. Original conceptual synthesis.

4 Matching membranes and pretreatment to industrial feedwaters

Membrane choice begins with a site-specific contaminant inventory rather than nominal pore size. Microfiltration and ultrafiltration primarily address suspended solids, colloids and certain microbial loads; nanofiltration generally provides selective removal of multivalent ions and many dissolved organics; RO provides stronger broad-spectrum dissolved-solute separation. Individual performance varies with membrane chemistry and solute properties. Experimental comparisons confirm that nanofiltration can approach RO rejection for some target contaminants while offering less removal of

particular monovalent ions [10]. The implication is not that one process supersedes another, but that treatment quality must be matched to actual reuse duties.

Wastewater segregation is an energy intervention because it prevents unnecessary dilution or contamination. Low-salt wash water should not automatically be blended with concentrated blowdown, especially when blending shifts the entire feed into a higher-pressure design class. Equalisation is valuable for smoothing flow, pH and conductivity, while targeted oil separation, coagulation, activated carbon or biological treatment can reduce the membrane fouling burden. The purpose of pretreatment is to establish stable membrane feed quality, not merely to achieve a single turbidity threshold; ultrafiltration cleaning and flushing also require operational optimisation [11]. A review of RO autopsies links plant failures to interacting foulants and inadequate characterisation, illustrating why a reassuring average feed analysis can conceal damaging excursions [12].

Organic-rich effluents require particular care. Colloids, extracellular polymers, soluble microbial products and multivalent ions can assemble into mixed deposits with different resistance and cleaning behaviour from any individual contaminant. Liu and colleagues documented such combined fouling in wastewater reuse, supporting integrated pretreatment based on foulant interactions [13]. For streams containing oils, solvents or oxidants, membrane material compatibility and process safety must precede performance projections. A chemical oxidation stage that removes colour may also expose polyamide membranes to harmful residual oxidant unless dechlorination is controlled. Consequently, chemical dosing should be monitored at defined sampling points instead of being considered a fixed accessory.

Membrane bioreactors (MBRs) can produce a relatively low-solids effluent upstream of high-pressure separation, but salinity and organic loading affect biological performance and membrane fouling. Saudi field-testing of produced-water desalination highlights the value of linking recovery technologies to process-water specifications [14]. This supports locally adapted pretreatment where wastewater chemistry permits stable performance; it does not establish that a single membrane process suits every petrochemical or high-salinity stream. Likewise, investigations of pretreatment in coal-chemical wastewater emphasise that mechanisms must be tested for the specific fouling mixture rather than transferred without validation [15].

Table 1. Feed-dependent membrane options and site-level verification requirements.

Industrial feed class	Plausible treatment path	Main operational hazard	Required evidence
Cooling-tower blowdown	Solids control → NF or RO	Scale formation; silica; ionic load	Scaling study; membrane trial
Biodegradable mixed effluent	Equalisation → MBR/UF → RO	Biofouling; organic carryover	Stable pretreatment; CIP record
Hydrocarbon-bearing wash water	Oil separation → polishing → RO	Organic attack; oil wetting	Compatibility; oil breakthrough
Highly saline process purge	Selective recovery → advanced RO/hybrid	Osmotic limit; brine volume	Full salt mass balance; residual route

5 Fouling diagnostics, cleaning and membrane life

Four principal failure families affect membrane trains: particulate deposition, inorganic scaling, organic adsorption and biological growth. Their effects may coexist, but each responds differently to

pressure, concentration polarisation, temperature and cleaning chemistry. Monitoring should therefore compare normalised permeate flow, differential pressure and normalised salt passage at fixed reference conditions. Declining flow with rising pressure loss is not equivalent to an isolated conductivity increase; the former may suggest deposits or hydraulic blockage, while the latter can reflect membrane damage, seal leakage or feed-composition shifts. Performance interpretation requires these signals to be examined together [12,16].

A robust operating record documents feed conductivity, organic indicators, silt-density or other appropriate fouling measures, recovery, permeate quality, reagent consumption and cleaning events. Sudden feed transitions deserve event-level annotation, because averaging may erase the causal link between industrial production cycles and membrane deterioration. Operators should use membrane-autopsy evidence selectively when routine measurements cannot distinguish scale, biofilm or chemical attack. Autopsy findings can identify mineral species and biological material, but do not automatically quantify which mechanism caused the largest energy penalty in the operating plant.

Cleaning-in-place restores performance only within the limits of membrane condition and compatible reagents. Unnecessary cleaning increases downtime, chemical use and possibly material ageing; delayed cleaning can consolidate deposits and raise hydraulic resistance. A condition-triggered protocol is consequently preferable to an arbitrary calendar whenever reliable monitoring exists. Pretreatment studies suggest that combined fouling cannot consistently be solved by simply increasing cleanings [13,15]. A cleaning trial should document normalised performance immediately before and after intervention, achieved recovery, effluent composition and chemical waste disposal. Failure to regain baseline performance should prompt root-cause investigation rather than repeated aggressive cleaning.

Membrane lifespan also has a circular-economy dimension. Reuse of retired high-rejection elements in less demanding applications has been explored experimentally, but potential contaminant carryover, hydraulic weakness and uncertain remaining life restrict automatic transfer to sensitive industrial services [17]. Lifecycle comparisons should include membrane manufacture, replacements, chemical consumption and end-of-life handling. Extending service life is beneficial only when the additional electricity and compromised product reliability do not outweigh avoided replacement impacts. Such trade-offs cannot be resolved by assessing rejection percentage alone.

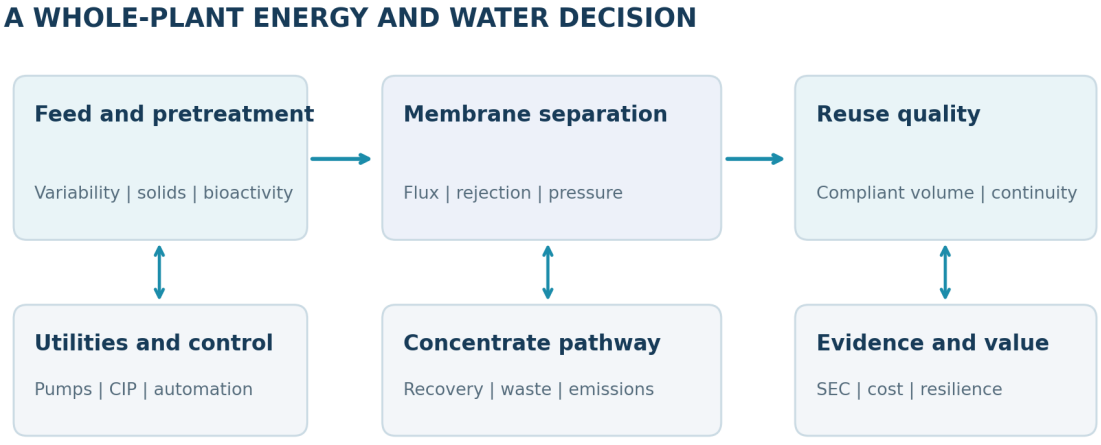

Figure 2. Coordinated measurement boundaries for whole-plant energy and water recovery. Original conceptual synthesis.

6 High-recovery configurations and concentrate management

Higher water recovery is attractive where intake capacity is constrained, water procurement is costly or liquid discharge creates environmental liability. Nevertheless, conventional serial RO stages can become inefficient as salinity, viscosity and osmotic pressure increase. Alternative architectures aim to regulate flux distribution and reduce overpressurisation. Hybrid semi-batch and batch arrangements have demonstrated favourable energy characteristics for specified brackish feeds in experimental and modelling work [18]. Closed-circuit RO operates through cyclic concentration and flushing; improved layouts attempt to preserve continuous useful production while limiting energetic penalties [19]. Both approaches increase the importance of valve sequencing, instrumentation and operator training.

Recent high-recovery research offers encouraging but bounded results. A proposed circle-sequence configuration sought to distribute flux more evenly and improve energy use for concentrated reuse feeds [20]. A later industrial tertiary-effluent pilot reported high recovery and energy advantages compared with a particular two-stage benchmark, while also noting that SEC increased as recovery rose [21]. These findings support pilot evaluation, not a universal recovery target. If silica precipitation, calcium salts or organic fouling governs the practical limit, control architecture alone cannot eliminate the chemistry. Each design therefore needs saturation modelling, antiscalant verification, concentrate sampling and a trial conducted across realistic feed variability.

Concentrate management must be addressed at concept design, because concentrating contaminants transfers rather than destroys them. Discharge, evaporation, crystallisation, selective precipitation and resource extraction have distinct regulatory, energy and capital implications. Reviews identify concentrate treatment as a major barrier to large-scale industrial recycling and caution against treating zero liquid discharge (ZLD) as intrinsically economical [22,23]. ZLD can be justified where disposal restrictions, scarce water supplies or valuable recovered salts outweigh thermal and chemical costs; elsewhere it may shift environmental burdens to solid-waste disposal and power generation. A mass balance should identify where every dissolved constituent eventually accumulates.

Hybrid membrane processes can extend recovery beyond RO limits. Membrane distillation may utilise appropriately priced low-grade heat, while electro-driven separation can offer selective ion management for suitable salinity ranges [24,25]. These options cannot be judged solely by the electric power measured at a membrane skid. Heating duty, cooling requirements, cleaning, membrane replacement and the usable value of recovered products must enter the same balance. Studies of innovative osmotic membranes indicate wider opportunities for mineral and energy recovery, but experimental selectivity and scalability remain important limitations [26]. For Saudi industrial complexes, co-location with waste-heat sources warrants investigation; its feasibility requires a measured heat profile rather than an assumed free supply.

Consider a hypothetical industrial estate with three streams: comparatively clean cooling blowdown, biodegradable wash water and a small high-salt process purge. Combining them upstream of one high-pressure train would simplify plumbing but could magnify the energy burden of treating the largest volume. Separate treatment might permit moderate-pressure recovery from the first stream, biological conditioning before RO for the second, and specialised concentrate management for the third. This is a design illustration, not a measured Saudi case. Its purpose is to expose the role of segregation in reducing avoidable pressure work and protecting shared membrane assets. The

preferred configuration would depend on site water balances, contamination risks and the economics of transferring treated water between users.

Implementation planning also needs contractual definitions of acceptable water. Specifications should identify sampling frequency, analytical methods, permissible excursions and who has authority to divert off-specification permeate. Conductivity alone is an inadequate acceptance indicator when the downstream process is vulnerable to trace organics, hardness, nutrients or microorganisms. For each proposed reuse route, engineers should prepare a cause-and-effect matrix connecting contaminant excursions with instrumentation, shutdown logic, alternative supply and residual storage. This turns nominal treatment performance into operational assurance. Operators also require a structured handover between production teams and water-treatment staff because upstream solvent losses, cleaning cycles or changes in raw materials can alter membrane feed more rapidly than periodic laboratory tests reveal. Establishing shared alarms and incident reviews therefore supports continuity as much as installing additional membrane area. In future Saudi demonstrations, publishing anonymised operating envelopes would improve independent comparability without requiring disclosure of commercially sensitive production recipes.

7 A Saudi-oriented treatment and governance framework

Industrial clusters within Saudi Arabia offer opportunities to connect water reuse with desalination, municipal treatment, energy infrastructure and process-heat networks. The most transferable planning principle is cascade reuse: reserve the highest-quality reclaimed water for demanding applications, then use less demanding services for appropriately treated lower-quality streams. Segregating cooling blowdown, condensate and chemical-processing effluents can prevent one problematic stream from determining the energy requirement of an entire facility. The proposed framework begins with a verified, seasonal inventory of flows and contaminants, followed by unit-specific product-water limits and documented opportunities for internal exchange.

The next decision gate classifies each stream according to treatability, process criticality and recovery potential. Relatively low-salinity streams may favour low-pressure RO or nanofiltration, while contaminated mixed effluents could require clarification and biological or physicochemical pretreatment. Highly saline residuals should be analysed for targeted recovery, off-site disposal or thermal concentration. Contaminant-rejection studies support selecting membranes by measured target removal rather than product labels [10]. In industrial districts, shared utility systems may improve utilisation and monitoring but can introduce contamination liability and contractual complexities. Responsibility for influent excursions, concentrate ownership and emergency diversion must consequently be assigned before commissioning.

Saudi planning should also recognise the distinction between desalination capacity and reuse demand. A coastal desalination plant can demonstrate efficient energy recovery without proving that the same architecture is optimal for inland industrial effluent. Regional reuse decisions must reflect conveyance distance, industrial water quality, available electricity, land and lawful disposal routes. The water-energy nexus literature stresses integration of membrane performance with energy and resource objectives [27]. Renewable power may reduce operating emissions, but its variability can challenge pressure stability and membrane preservation. Storage, coordinated operating schedules and grid support should be appraised together rather than assuming solar supply automatically minimises lifecycle cost [28].

Governance extends beyond technical compliance. A reuse scheme needs transparent custody of samples, calibrated instruments, a validated chemical management programme and contingency water supply when membranes are unavailable. Acceptance of reuse depends on trust, management and end-use clarity, even when public-perception findings cannot be extrapolated directly to industrial procurement [29]. A Saudi-oriented management framework should therefore connect operator training, laboratory assurance and energy audits to a documented decision authority. Its value lies in defining reproducible control points rather than proposing a generic digital platform as a substitute for engineering oversight.

Sensitivity analysis should accompany financial claims. A credible feasibility study varies electricity price, membrane replacement intervals, chemical dosing, usable recovery, brine disposal cost and the fraction of water that meets specification. Scenario testing should also account for production interruptions and the price of emergency makeup water. A project that performs well at steady design load may become unattractive at partial utilisation if fixed aeration or circulation energy dominates. Conversely, a somewhat costlier modular system may offer measurable advantages where outages cause major downstream losses. Transparent reporting of these assumptions is more useful than transferring cost-per-cubic-metre figures between dissimilar facilities. Sensitivity ranges should be justified by site records or explicitly labelled exploratory.

Table 2. Proposed quantitative reporting metrics for Saudi industrial membrane reuse projects.

Evaluation variable	Proposed definition or method	Decision relevance
Net recovery (%)	Reuse-compliant volume ÷ total incoming wastewater × 100	Avoids membrane-only recovery inflation
Whole-plant SEC (kWh/m^3)	Total relevant electricity ÷ compliant reused volume	Comparable energy boundary
Quality compliance (%)	Pass samples ÷ total valid samples × 100	Protects actual industrial end use
Downtime and cleaning	Unavailable hours; CIP cycles per operating interval	Tests long-term reliability
Residual burden	Concentrate mass, chemical waste, sludge and discharge quality	Tests displacement of environmental impact
Lifecycle value	Capital, operation, waste and outage costs over plant life	Supports staged investment

8 Evaluation metrics and evidence-based commissioning

Commissioning should establish a defensible baseline before benefits are claimed. The minimum dataset includes hourly feed and permeate flows, concentrations, pressures, temperature, individual motor power, cleaning events, rejected product and final reuse demand. Net reusable-water recovery should be calculated from the inlet of the overall treatment train, not solely across the final RO stage. Similarly, plant-level SEC should use electricity consumed by all relevant equipment divided by compliant reused water. Normalisation enables comparison across feed changes, but any excluded utilities must be reported. Without a common boundary, an apparent energy improvement can result from moving treatment duties to another unit.

Environmental evaluation should combine freshwater displacement, electricity-related emissions, chemical consumption, brine production, residual toxicity and sludge management. Industrial sus-

tainability analyses demonstrate that UF–RO electricity can materially affect lifecycle impacts even when reuse improves water availability [30]. Reported benefits should be tested against realistic marginal grid electricity, plant utilisation and transport distances. A higher recovery ratio may improve water security but produce more concentrated and expensive residuals. Reporting both outcomes avoids a misleading single-number success narrative.

Techno-economic analysis should separate upfront equipment, membrane replacement, reagent procurement, energy, labour, waste handling and outage costs. Discount rate, tariff structure, expected utilisation and feed composition require transparent assumptions. A high-recovery pilot may indicate technical feasibility while leaving commercial competitiveness unresolved. Benchmark comparisons should therefore be conditional on the same product-quality requirement and equivalent boundaries. For an industrial buyer, a slightly higher treatment cost may be defensible if predictable water supply prevents expensive interruption, yet that reliability premium must be evaluated rather than asserted.

A staged acceptance test should include stable baseline operation, controlled feed excursions, cleaning recovery, failure response and a sustained validation interval. Results should be independently traceable to metered flows and laboratory certificates. Decision thresholds can then be assigned to SEC, compliant production, downtime, membrane integrity and concentrate discharge. This creates an investment sequence in which proven improvements are expanded progressively, rather than assuming that simulated maximum recovery represents dependable industrial service.

9 Research gaps and critical discussion

The literature offers stronger evidence for individual components than for the entire Saudi industrial reuse chain. Seawater energy studies frequently use relatively stable feed chemistry and mature high-pressure configurations, whereas industrial effluents are mixtures shaped by changing operations. Conversely, wastewater reuse experiments may document excellent rejection or recovery without reporting cumulative electricity, cleaning chemicals, concentrate handling and long-duration availability. Direct comparison is consequently vulnerable to boundary mismatch. Future research should report paired energy and contaminant mass balances and record whether the treated water actually replaces purchased freshwater.

The second gap concerns the scale and representativeness of trials. Short pilot studies identify operating mechanisms but may not capture seasonal variation, long-term biofouling, abrupt industrial spills or membrane ageing. High-recovery results should be tested against minimum and maximum feed loads, realistic outage scenarios and concentrate composition over extended operation. Local work on saline industrial MBR treatment underscores the need to validate feed-dependent pretreatment under Saudi conditions [14]. Multi-facility datasets would support more credible design ranges than isolated best-performing operating points.

Third, decarbonisation and resilience goals can conflict with a narrow focus on minimum instantaneous electricity. Frequent on-off cycling to follow renewable generation may accelerate membrane stress, while an insistence on extreme water recovery may amplify downtime risk. The appropriate objective is therefore a constrained operational optimum combining dependable reuse output, emissions, lifetime cost and discharge compliance. Technological reviews of hybrid systems and ERDs emphasise important possibilities but also implementation obstacles [8,24]. Digital optimisation should be introduced only after sensors, material balances, alarms and operator override procedures are dependable.

Finally, the literature has limited comparable evidence on residual toxicity, salt marketability and allocation of environmental responsibility across shared industrial water networks. A circularity claim requires proof that recovered salt or water has a specified use and that rejected substances remain controlled. The strongest near-term research agenda is interdisciplinary: membrane science to explain separation, process engineering to establish energy balances, environmental analysis to identify burden shifting, and operations research to test robust plant control. Such integration could convert promising laboratory concepts into Saudi projects with measurable and defensible performance.

Future trials should report the duration of stable operation, the number of cleaning cycles and the variability of inlet chemistry, because short demonstrations can overestimate dependable recovery. Comparable reporting would help distinguish technological potential from achievable service.

10 Conclusions

Reverse osmosis can substantially support industrial water recovery in Saudi Arabia when it is deployed as part of a feed-specific reuse system rather than an isolated desalination unit. The reviewed studies support four conclusions. First, membrane selection must follow the intended water duty and the complete contaminant profile. Second, energy reduction requires simultaneous control of hydraulic losses, membrane fouling, recovery and auxiliary treatment, with pressure recovery adopted only where justified by available concentrate energy. Third, high-recovery architectures and hybrid technologies are promising but require careful treatment of scaling, operational variability and concentrate destinations. Fourth, credible environmental and economic benefits depend on measuring compliant reused water across a consistent whole-plant boundary.

The proposed framework links segregation, pretreatment, separation, energy optimisation and residual management through evidence-based commissioning and explicit accountability. Its immediate use is to structure feasibility studies and pilot specifications for Saudi industrial sites; it is not a validated prediction of national water savings. Future research should prioritise long-duration local operating data, comparable lifecycle metrics and trials demonstrating reliable reuse under variable industrial conditions. A technically successful membrane plant is ultimately one that supplies the right water, at defensible energy and environmental cost, throughout its expected service life.

References

[1] Eke, J., Yusuf, A., Giwa, A., and Sodiq, A. (2020). The global status of desalination: An assessment of current desalination technologies, plants and capacity. *Desalination*, 495, 114633. https://doi.org/10.1016/j.desal.2020.114633

[2] Park, K., Kim, J., Yang, D. R., and Hong, S. (2020). Towards a low-energy seawater reverse osmosis desalination plant: A review and theoretical analysis for future directions. *Journal of Membrane Science*, 595, 117607. https://doi.org/10.1016/j.memsci.2019.117607

[3] Alanezi, A. A., Altaee, A., and Sharif, A. O. (2020). The effect of energy recovery device and feed flow rate on the energy efficiency of reverse osmosis process. *Chemical Engineering Research and Design*, 158, 12–23. https://doi.org/10.1016/j.cherd.2020.03.018

[4] Panagopoulos, A., and Haralambous, K.-J. (2020). Environmental impacts of desalination and brine treatment: Challenges and mitigation measures. *Marine Pollution Bulletin*, 161, 111773. https://doi.org/10.1016/j.marpolbul.2020.111773

[5] Shah, S. R., and Winter, A. G. (2023). Evaluating the production and exergetic performance of point-of-use reverse osmosis devices for brackish water desalination. *Desalination and Water Treatment*, 302, 1–14. https://doi.org/10.5004/dwt.2023.29729

[6] Schunke, A. J., Herrera, G. A. H., Padhye, L., and Berry, T.-A. (2020). Energy recovery in SWRO desalination: Current status and new possibilities. *Frontiers in Sustainable Cities*, 2, 9. https://doi.org/10.3389/frsc.2020.00009

[7] Lou, F., Nie, S., Yin, F., Lu, W., Ji, H., Ma, Z., and Kong, X. (2022). Numerical and experimental research on the integrated energy recovery and pressure boost device for seawater reverse osmosis desalination system. *Desalination*, 523, 115408. https://doi.org/10.1016/j.desal.2021.115408

[8] Wang, C., Wang, S., Wang, K., Xiao, Y., Ma, Q., Song, D., Wang, R., and Zhang, Y. (2024). Developmental impediment and prospective trends of desalination energy recovery device. *Desalination*, 578, 117465. https://doi.org/10.1016/j.desal.2024.117465

[9] Ruiz-García, A., Nuez, I., and Khayet, M. (2023). Performance assessment and modeling of an SWRO pilot plant with an energy recovery device under variable operating conditions. *Desalination*, 555, 116523. https://doi.org/10.1016/j.desal.2023.116523

[10] Alhussaini, M. A., Souza-Chaves, B. M., Felix, V., and Achilli, A. (2024). Comparative analysis of reverse osmosis and nanofiltration for the removal of dissolved contaminants in water reuse applications. *Desalination*, 586, 117822. https://doi.org/10.1016/j.desal.2024.117822

[11] Oron, G., Gillerman, L., Buriakovsky, N., and Bick, A. (2024). Modeling of spiral wound ultrafiltration membrane forward flushing during secondary wastewater upgrading for unrestricted irrigation. *Desalination*, 573, 117129. https://doi.org/10.1016/j.desal.2023.117129

[12] Philibert, M., Villacorte, L. O., Ekowati, Y., Abushaban, A., and Salinas-Rodriguez, S. G. (2024). Fouling and scaling in reverse osmosis desalination plants: A critical review of membrane autopsies, feedwater quality guidelines and assessment methods. *Desalination*, 592, 118188. https://doi.org/10.1016/j.desal.2024.118188

[13] Liu, X.-Y., Chen, Y.-B., Fu, J., Zhu, X., Lv, L.-Y., Sun, L., Zhang, G.-M., and Ren, Z.-J. (2024). A review of combined fouling on high-pressure membranes in municipal wastewater reuse: Behaviors, mechanisms, and pretreatment mitigation strategies. *Chemical Engineering Journal*, 485, 150135. https://doi.org/10.1016/j.cej.2024.150135

[14] Ahmed, S. A., Al-Jeshi, M. A., and Al-Yousef, K. K. (2022). Produced water reuse enabling circularity in oil operations. *Desalination and Water Treatment*, 263, 60–69. https://doi.org/10.5004/dwt.2022.28223

[15] Tang, P., Shi, J., He, C., Li, X., Chen, G., Deng, Y., Qin, J., and Liu, B. (2025). Mitigation effect and mechanism of different pretreatment methods on reverse osmosis membrane fouling in coal chemical wastewater treatment. *Desalination*, 598, 118437. https://doi.org/10.1016/j.desal.2024.118437

[16] Tayeh, Y. A. (2024). A comprehensive review of reverse osmosis desalination: Technology, water sources, membrane processes, fouling, and cleaning. *Desalination and Water Treatment*, 320, 100882. https://doi.org/10.1016/j.dwt.2024.100882

[17] Giraldo Mejía, H. F., Toledo-Alarcón, J., Rodríguez, B., et al. (2022). Direct recycling of discarded reverse osmosis membranes for domestic wastewater treatment with a focus on water reuse. *Chemical Engineering Research and Design*, 184, 473–487. https://doi.org/10.1016/j.cherd.2022.06.031

[18] Hosseinipour, E., Karimi, S., Barbe, S., Park, K., and Davies, P. A. (2022). Hybrid semi-batch/batch reverse osmosis (HSBRO) for use in zero liquid discharge (ZLD) applications. *Desalination*, 544, 116126. https://doi.org/10.1016/j.desal.2022.116126

[19] Li, M. (2023). An improved closed-circuit RO (CCRO) system: Design and cyclic simulation. *Desalination*, 554, 116519. https://doi.org/10.1016/j.desal.2023.116519

[20] Lee, Y., Kang, W., Lee, W., Lee, J. H., and Kim, J. (2024). Improving water flux distribution and energy efficiency in reverse osmosis for high-recovery water reuse. *Desalination*, 585, 117779. https://doi.org/10.1016/j.desal.2024.117779

[21] Lee, Y., Kang, W., Lee, W., Park, M.-J., and Kim, J. (2025). Pilot study of circle sequence reverse osmosis for high-recovery water reuse in industry using tertiary effluent. *Desalination*, 600, 118480. https://doi.org/10.1016/j.desal.2024.118480

[22] Patel, R. V. P., and Raval, H. (2024). Comparative assessment of treatment technologies for minimizing reverse osmosis concentrate volume for industrial applications: A review. *Water Science and Technology*, 90, 314–343. https://doi.org/10.2166/wst.2024.218

[23] Abdelfattah, I., and El-Shamy, A. M. (2024). Review on the escalating imperative of zero liquid discharge (ZLD) technology for sustainable water management and environmental resilience. *Journal of Environmental Management*, 351, 119614. https://doi.org/10.1016/j.jenvman.2023.119614

[24] Al-Obaidi, M., Alsarayreh, A. A., Rashid, F. L., Sowgath, M. T., Alsadaie, S., Ruiz-García, A., Khayet, M., Ghaffour, N., and Mujtaba, I. M. (2024). Hybrid membrane and thermal seawater desalination processes powered by fossil fuels: A comprehensive review, future challenges and prospects. *Desalination*, 583, 117694. https://doi.org/10.1016/j.desal.2024.117694

[25] Deemer, E. M., Xu, P., Verduzco, R., and Walker, W. S. (2023). Challenges and opportunities for electro-driven desalination processes in sustainable applications. *Current Opinion in Chemical Engineering*, 42, 100972. https://doi.org/10.1016/j.coche.2023.100972

[26] Nguyen, D. V., and Wu, D. (2024). Recent advances in innovative osmotic membranes for resource enrichment and energy production in wastewater treatment. *Science of the Total Environment*, 927, 172153. https://doi.org/10.1016/j.scitotenv.2024.172153

[27] Politano, A., Al-Juboori, R. A., Alnajdi, S., et al. (2024). 2024 roadmap on membrane desalination technology at the water-energy nexus. *Journal of Physics: Energy*, 6, 021502. https://doi.org/10.1088/2515-7655/ad2cf2

[28] Kettani, M., and Bandelier, P. (2020). Techno-economic assessment of solar energy coupling with large-scale desalination plant: The case of Morocco. *Desalination*, 494, 114627. https://doi.org/10.1016/j.desal.2020.114627

[29] Asaad, S., and Suleiman, A. (2023). Socio-demographic factors and treated wastewater reuse in the MENA region: Insights and implications. *Desalination*, 565, 116830. https://doi.org/10.1016/j.desal.2023.116830

[30] Zhang, S., Li, D., Yao, P., Huang, G., Zhang, Z., Wang, Z., Shi, Y., Zhao, J., and Qian, G. (2024). Assessing the sustainability of wastewater reuse and derivative waste recovery system in integrated circuit enterprise. *Chemical Engineering Journal*, 499, 155777. https://doi.org/10.1016/j.cej.2024.155777