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Review Article

Smart Industrial Water Utilization and Zero Liquid Discharge Technologies for Sustainable Chemical Manufacturing in Saudi Arabia

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Abstract: Saudi chemical manufacturing depends on reliable water supplies for reaction media, steam generation, cooling, cleaning and utility services, yet conventional wastewater management often treats these interconnected demands as separate engineering problems. This critical review evaluates how intelligent water allocation, selective treatment and zero liquid discharge can be combined without assuming that maximum water recovery necessarily produces the best environmental outcome. Thirty peer-reviewed publications dated 2020–2025 were examined across industrial water networks, petrochemical effluent reclamation, membrane desalination, concentrate treatment, crystallisation and digital process control. Their evidence is interpreted for Saudi industrial clusters rather than presented as results from an unperformed local field study. The synthesis identifies four interdependent decisions: segregating streams before contamination is diluted; matching recovered water to explicit quality requirements; shifting the highest feasible proportion of desalination upstream of thermal concentration; and controlling residual solids, energy demand and operational reliability. A staged configuration integrates water accounting, biological or physicochemical pretreatment, ultrafiltration, reverse osmosis, selective polishing and final brine management. Digital monitoring can improve early detection of scaling, membrane deterioration and abnormal water losses, but models require calibration against site-specific chemistry. The review proposes a water–energy–salt decision framework and a validation agenda for Saudi chemical facilities. Its central conclusion is that genuinely sustainable discharge elimination requires accountable material balances, end-use protection and credible management of the recovered salt, not simply the installation of an evaporator.

Keywords: Industrial Water Reuse, Zero Liquid Discharge, Chemical Manufacturing, Saudi Arabia, Membrane Separation, Brine Valorisation, Digital Monitoring, Circular Water Systems.

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1. INTRODUCTION

Water reliability has become an industrial competitiveness issue rather than merely an environmental compliance consideration. Chemical production requires water at differing qualities, from relatively tolerant cooling applications to demineralised boiler feed and highly controlled process-contact duties. In Saudi Arabia, climatic aridity and dependence on engineered water supplies make avoidable withdrawals especially consequential. A national assessment of wastewater reuse argues that treated effluent is an increasingly important supply resource, while acknowledging infrastructure and utilisation constraints [1]. For integrated chemical complexes, the strategic

opportunity is to circulate each water stream through successive appropriate duties instead of paying repeatedly to produce high-purity water and subsequently treating mixed effluent.

Zero liquid discharge (ZLD) is frequently presented as the logical endpoint of industrial water stewardship. However, it denotes the prevention of liquid effluent leaving a defined system boundary; it does not demonstrate that energy consumption, solid residuals or greenhouse-gas emissions have been minimised. Evaluations of ZLD deployment distinguish water recovery from the total burdens of evaporation and salt handling [2]. The economic justification also changes with local water tariffs, energy prices, industrial siting and the chemical complexity of reject streams. A theoretically closed water loop may therefore be less sustainable than a carefully governed minimum-liquid-discharge arrangement under some conditions.

The chemical sector presents particular barriers to generic solutions. Wastewater can include variable salinity, alkaline or acidic cleaning liquors, hydrocarbons, suspended catalyst fines, solvents, phenolic compounds and difficult-to-oxidise organic carbon. Combining these streams prematurely increases the duty imposed on every downstream unit. Evidence from petrochemical treatment demonstrates that staged separation and biological conditioning can prepare wastewater for membrane recovery, but does not establish universal performance across different factories [3]. At the same time, membrane desalination generates an increasingly concentrated reject whose scaling behaviour cannot be inferred from salinity alone [4]. These interactions make plantwide design more important than isolated technology comparisons.

This review asks a precise question: under what feedwater, utility and operational conditions can smart allocation and hybrid treatment improve water security in Saudi chemical manufacturing while making a defensible case for ZLD? Its contribution is an integrated decision logic linking source management, product-water specifications, concentration limits, heat integration, digital assurance and solid-residue quality. The argument deliberately separates published observations from proposed Saudi applications, and avoids translating overseas pilot outcomes into unsupported national forecasts.

Importantly, the language of zero discharge must be handled with care. A review of recovery-oriented ZLD systems distinguishes complete treatment trains from individual reclamation units and shows that high apparent reuse does not by itself resolve final concentrates [5]. The practical boundary for this paper includes treatment equipment, shared storage, occasional off-specification diversions and offsite residual handling. A system is not considered closed merely because wastewater is transferred by tanker to another operator. Equally, recycled water should be assessed against the fresh water it genuinely displaces, after allowing for dilution water, cleaning requirements and any compensating changes to cooling or boiler operation.

2. Review Aim, Objectives and Analytical Method

The aim is to establish a technically grounded framework for conserving industrial water and assessing whether final brine elimination is justified within Saudi chemical manufacturing. Four objectives guide the appraisal: first, identify preventable demand and opportunities for direct water exchange; second, compare treatment sequences by contaminant chemistry and required reuse quality; third, examine the energy, scaling and solids constraints on ZLD; and fourth, specify measurable digital and economic conditions for implementation. Unlike a technology inventory, the unit of analysis is the combined water network, including the residual mass that treatment displaces.

A structured critical narrative approach was adopted, drawing on thirty identifiable peer-reviewed journal publications from 2020–2025. Sources were selected for direct relevance to water-network optimisation, chemical or petrochemical reuse, high-salinity separation, crystallisation, resource recovery, process control or Saudi water conditions. The evidence was grouped into source reduction, conditioning, desalination, terminal brine treatment, digital operations and evaluation. Contradictory findings were retained where different water matrices, scales or cost boundaries plausibly explain them. This is not a pooled statistical meta-analysis: incompatible experiments and techno-economic assumptions cannot support a single mean recovery rate. No database-screening totals or field measurements are claimed.

Each technical option was assessed against six criteria: incoming contaminant envelope; intended outlet quality; freshwater displacement; energy and chemical inputs; treatment of residual liquids and solids; and operational sensitivity. Economic arguments were considered transferable only when the assumed feed composition, power source, plant scale and by-product market could be matched locally. A previous comparison of alternative ZLD trains illustrates why energy and recoverable water must be reported alongside the fate of evaporated water [6]. The review consequently uses conditional recommendations and mass-balance definitions rather than presenting

schematic performance values as experimental findings.

3. Characterising Water Demand and Wastewater Sources

An industrial water audit should begin at the consumption point. Cooling-tower make-up is governed principally by scaling, corrosion and biological control, whereas boiler feed may require very low conductivity and silica. Direct reuse of a moderately saline but otherwise clean stream may be suitable for one service and hazardous for another. Process-contact water introduces further restrictions where trace metals, organics or microbial contamination affect catalysts or product purity. Mapping these needs separately prevents the common mistake of imposing a single expensive polishing specification on all reclaimed water.

Water balance closure then distinguishes genuine consumption from leakage, evaporation, export in products and intentional blowdown. Metered withdrawal alone says little about internal circulation or the effect of production scheduling. Lyu and colleagues propose industrial water accounting that connects measurement, auditing and enterprise decisions [7]. The practical implication is to reconcile inlet and outlet data at both unit-operation and plant boundaries. Monthly totals can conceal short contamination events, whereas excessively granular dashboards without reconciliation may mislead operators. A usable accounting system records source, flow, conductivity, organic loading, temperature, reuse destination and uncertainty.

Stream segregation is frequently more effective than end-of-pipe chemical addition. Relatively clean cooling blowdown, membrane concentrate, solvent-bearing production wastewater and concentrated cleaning solutions should not automatically share the same collection header. Segregation protects biological treatment from inhibitory shocks and reduces the unnecessary concentration of organics in saline brines. It also preserves opportunities for selectively recovering salts or chemicals. Demonstration work on chemically complex wastewater has examined treatment of highly saline streams and reverse-osmosis concentrates together, highlighting the importance of hardness management before recycling [8]. Such findings support site-specific classification, not blanket separation of every possible flow.

The water–salt balance is equally important. If freshwater recovery rises while the mass of dissolved salts remains approximately constant, the rejected stream becomes more concentrated and potentially less manageable. Recovering 80% of the feed as permeate does not remove the need to manage the remaining 20%; its chemistry may be substantially more challenging. Scaling indices should therefore be estimated for calcium carbonate, calcium sulphate, silica and other relevant salts under actual temperature and pH conditions. Changes in production grade, cleaning frequency and seasonal cooling demand warrant separate characterisation campaigns rather than an annual composite sample.

A separate concern is trace contaminant transfer. A cooling circuit may tolerate moderate dissolved solids but remain vulnerable to volatile organic compounds, corrosive species or organisms capable of colonising heat-transfer surfaces. Similarly, a plant that manufactures several chemical grades cannot assume that the same recycled stream is equally suitable for all recipes. Local process-hazard reviews should specify conditions triggering automatic diversion, the minimum analytical detection capability and the personnel authorised to restore water circulation. Such checks make water integration a process-safety decision as well as a resource-conservation measure.

4. Smart Allocation before Advanced Treatment

The most economical recovered cubic metre is often the one that requires no additional desalination. Multi-contaminant water-network targeting demonstrates that reuse decisions must satisfy several concurrent quality limits rather than optimising a single pollutant [9]. In chemical facilities, a low-salinity rinse could supply an earlier washing stage, while suitable condensate may be returned to a steam system after safeguarding against carryover. Heat and mass integration must be evaluated together: exchanging hot wastewater for cold process feed can save energy, but transferring contaminants into sensitive equipment negates that benefit.

Source–sink matching should therefore proceed through explicit constraints. Candidate exchanges need acceptable ranges for conductivity, total organic carbon, suspended solids, temperature and any process-specific inhibitor. The decision is not binary reuse versus disposal; it includes direct cascade, equalisation, limited polishing, advanced desalination and controlled rejection. Nonlinear scheduling matters because a receiver may demand water precisely when a donor is not operating. Buffer storage, operational flexibility and contingency supply can become more important than theoretical maximum network connectivity.

Industrial audits should distinguish gross circulation from net freshwater displacement. Recirculating already recovered water through an additional treatment skid can increase reported

treatment throughput without reducing make-up. A meaningful performance ratio relates avoided external withdrawal to the site's baseline production-normalised demand. Water accounting also needs a stable production denominator: tonnes of chemical product may be reasonable within a plant but can distort comparisons between products with radically different water duties. Consequently, a cluster-level benchmark should report separate utility and production-water indicators rather than a single industry-wide efficiency score.

5. Reuse-Oriented Pretreatment and Membrane Trains

Biological and physicochemical treatment prepare the feed for selective desalination; neither can generally remove dissolved salts sufficiently to close the water loop. In petrochemical wastewater, coagulation followed by a moving-bed biofilm reactor reduced biodegradable organic loading in a staged pilot investigation [3]. The mechanistic benefit lies in limiting the accumulation of organics on downstream membranes, not in guaranteeing a particular desalination recovery. Oils, surfactants and solvents must be considered individually because compounds with similar bulk chemical oxygen demand can exhibit very different fouling tendencies.

Ultrafiltration removes colloidal matter and suspended solids ahead of high-pressure membranes, while reverse osmosis (RO) provides the principal dissolved-salt barrier for many moderate-salinity streams. A petrochemical demonstration combining ultrafiltration, RO and electrodeionisation produced high-quality water for industrial reuse under its tested conditions [10]. Electrodeionisation should consequently be considered a targeted finishing step for stringent applications, not a universal part of every reclaimed-water train. The final architecture depends on whether the product is destined for cooling, non-contact washing, steam generation or direct process use.

Membrane selection is constrained by the feed's osmotic pressure and scaling propensity. A critical review of high-salinity technologies identifies concentration limits, fouling and operational complexity as fundamental differentiators between pressure-driven and alternative processes [11]. The recoverable fraction is thus a function of individual ion activities as well as total dissolved solids. Selecting a greater pressure rating cannot by itself overcome precipitation and irreversible membrane damage. Pretreatment may include clarification, softening, adsorption, pH control or selective organics destruction; the order must reflect whether the limiting foulant is particulate, organic, biological or inorganic.

Advanced membrane materials are promising but require careful evidence interpretation. Studies have demonstrated improved anti-scaling characteristics with ceramic-supported graphene membranes during challenging industrial wastewater treatment [12]. Reviews of membrane surface engineering nevertheless note persistent difficulties associated with mixed foulants and long-term surface stability [13]. Laboratory rejection values cannot be transferred directly to a refinery or chemical factory with variable cleaning chemicals, microbial excursions and harsh temperature cycles. Pilot acceptance tests must therefore include sustained flux, cleaning recovery, product-water consistency and end-of-life membrane management.

6. Concentrate Minimisation and the ZLD Boundary

Alternative thermal schemes should be assessed for their response to climatic and spatial restrictions. Open evaporative options can reduce purchased energy but introduce land demand, airborne salt risks and uncertainty about actual water recovery. An appraisal of brine treatment and denitrification cautions that zero-discharge designs must still manage environmental trade-offs and the composition of reject streams [14]. In a densely occupied industrial cluster, covered crystallisation may be preferable despite higher equipment costs. Where seasonal humidity or dust affects exposed ponds, nominal evaporation capacity is a poor substitute for measured, weather-normalised performance. These issues should be resolved before financial claims are made for passive concentration.

After efficient upstream reuse, the residual concentrate determines whether ZLD is practicable. Its treatment should not begin with the assumption that one crystalliser suits all wastewaters. The relevant variables include salinity, sulphate hardness, silica, organic carbon, corrosion potential and the availability of low-grade heat. A broad assessment of brine technologies emphasises that thermal and membrane processes have complementary operating windows [15]. The preferred route usually shifts as the remaining solution approaches solubility limits and becomes progressively harder to process through conventional pressure membranes.

Electrodialysis and related electrically driven separations can play a useful intermediary role where ion composition permits concentration or separation without excessive scaling. Electrodialysis metathesis has been investigated for difficult high-salinity wastewater, with stream conversion supporting subsequent salt recovery [16]. However, electrical efficiency, membrane selectivity and pre-existing hardness vary with feed chemistry. These

approaches warrant comparison against high-pressure RO, membrane distillation and direct thermal concentration on an equal water and salt balance, not through isolated claims about specific energy consumption.

Membrane distillation exploits a vapour-pressure difference and can use recoverable thermal energy; nonetheless, membrane wetting and crystallisation at the surface complicate prolonged operation. Reviews of membrane-distillation crystallisation identify the potential for integrated water and solid recovery alongside persistent pore-wetting, scaling and financial limitations [17]. Electrical surface interventions have also been explored to mitigate mineral deposition, although evidence from controlled experimental systems is not equivalent to proof of industrial-scale resilience [18]. These technologies should be treated as candidate intensification stages rather than replacements for water-quality monitoring and pretreatment.

Terminal evaporation and crystallisation provide a more direct route to solids, but require substantial utility input and corrosion-resistant equipment. An assessment comparing alternative ZLD schemes found materially different outcomes depending on crystallisation strategy and assumptions about water collection [6]. An additional analysis of hybrid brine recovery demonstrated the sensitivity of economic results to the chosen crystallisation method and coproduct accounting [19]. The important distinction is between evaporating residual water to the atmosphere and condensing it for return to the plant: both may reduce liquid discharge, but only the latter adds reusable water to the balance.

Solid generation also deserves greater scrutiny. Mixed salts containing organic compounds, heavy metals or treatment additives cannot automatically be sold as useful chemical feedstocks. Research on eutectic freeze crystallisation combined with bipolar-membrane electrodialysis demonstrates a potential route for recovering selected salts and producing acid and alkali streams under controlled conditions [20]. Nevertheless, site-specific purity, separation expenditure, shipping requirements and buyer acceptance determine whether a material is a product or waste. Unsold solids still demand regulated containment; replacing wastewater disposal with uncontrolled salt stockpiles is not circular manufacturing.

7. Digital Control, Diagnostics and Operational Trust

Forecasting quality is also difficult when the most important variables are sampled infrequently. Research comparing artificial-intelligence methods for effluent prediction indicates that extensive multiyear datasets can improve forecasting while remaining tied to the characteristics of the studied treatment facility [21]. For industrial deployment, model validation must separate training periods from unseen production campaigns, including maintenance outages and composition shifts. Reporting a high correlation for routine operating data is insufficient if rare high-consequence events are missed. Operators need calibrated prediction intervals and rules specifying when a physical instrument or laboratory result supersedes a model estimate.

Smart utilisation requires a digital model of flows and quality, but installing sensors does not by itself create a reliable decision system. Online conductivity, pH, temperature, flow, pressure, turbidity and selected organic indicators can identify developing abnormalities. Some constituents, particularly trace product contaminants and specific scaling precursors, still require validated laboratory analysis. Digital-twin reviews explain the value of combining live instrumentation with process models, while warning that data quality and model maintenance remain major barriers [22]. The appropriate starting point is a reconciled plant balance with verified instruments.

Machine-learning models can forecast membrane pressure rise, effluent variability or treatment demand, but they should not issue unchecked commands. A review of deep learning in wastewater modelling notes the tension between flexible prediction and limited, inconsistent training data [23]. Hybrid models offer a more defensible route: physical mass balances constrain predictions, while statistical components represent nonlinear relationships that conventional equations omit. Alarm thresholds should reflect water-quality risk and control-room response time rather than a universal model accuracy score.

For membrane trains, useful indicators include normalised permeate flow, differential pressure, salt passage, cleaning frequency and membrane age. For crystallisers, temperature profiles, supersaturation estimates, compressor duty and solids characteristics are more informative than an isolated discharge metric. Recent analysis of artificial intelligence for membrane treatment describes opportunities in fouling prediction and operating optimisation but also highlights integration challenges [24]. Practical model deployment must therefore specify sensor drift checks, retraining frequency, failure modes, cybersecurity boundaries and an operator override mechanism.

Advanced predictive control is attractive for managing interacting treatment stages. Machine-learning and control studies have shown potential to improve operational efficiency in treatment systems [25]; that evidence should not be interpreted as a verified savings percentage for a Saudi chemical plant. The most credible use case is early detection of a change in feed composition followed by a bounded response: divert the affected stream, moderate membrane recovery, increase sampling or schedule controlled cleaning. Such actions protect the system against abrupt deterioration while preserving transparent accountability for final operational decisions.

8. Integrated Framework for Saudi Chemical Manufacturing

Figure 1 assembles the proposed plant-level architecture. Production units first undergo source–sink auditing, allowing low-risk direct exchanges before wastewater enters common treatment. Remaining streams are separated into relatively clean saline water, biodegradable organic wastewater and highly contaminated or episodic waste. Pretreatment then supports fit-for-purpose desalination. Product water passes application-specific verification, while concentrate follows a separately engineered salt-management route. The arrangement is intentionally modular because industrial parks contain different product lines, historical utilities and land constraints.

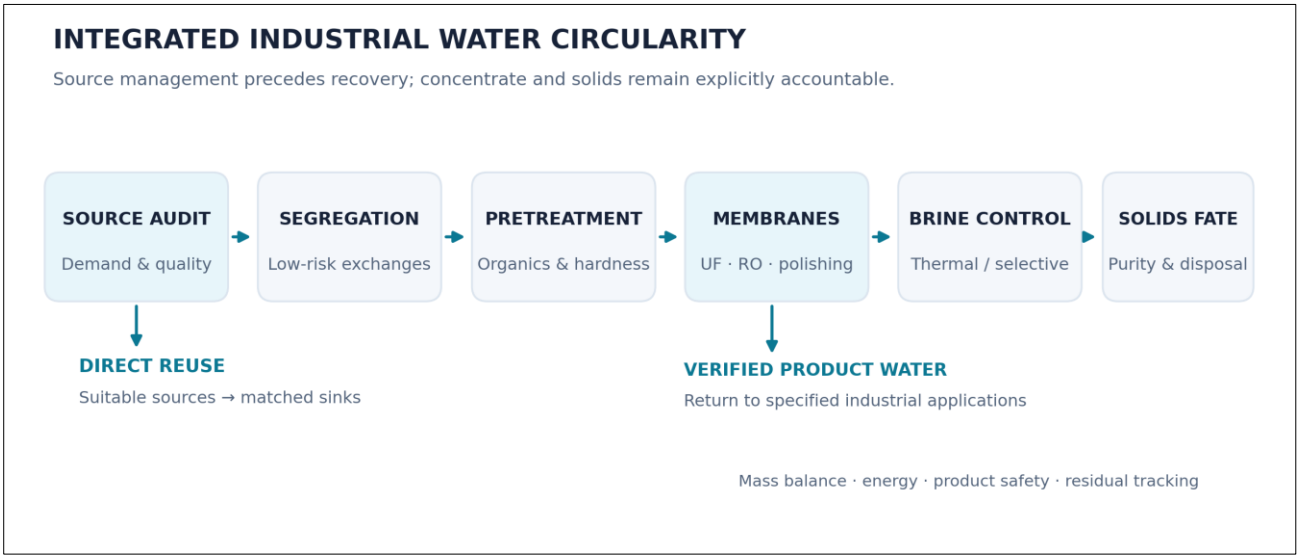


Figure 1: Proposed source-to-residual industrial water framework. Original conceptual schematic; arrows show decisions, not measured flow rates

Water governance should specify the ownership of every recovered stream. Utility operators may control cooling and steam systems, whereas production teams determine acceptable trace contaminants. Environmental teams assess the residual fate, and commercial staff can evaluate salt sales only after a credible purity assessment. These organisational boundaries matter especially in shared industrial clusters, where a stream suitable for one factory may be unsuitable for another. The proposed framework therefore allows offsite exchanges only after contractual quality, liability and continuity conditions have been demonstrated.

Table 1 compares the main treatment stages using qualitative, evidence-based boundaries rather than artificially precise recovery percentages. The table is intended for screening; hydraulic modelling and pilot studies remain necessary before technology procurement. Figure 2 presents a decision pathway that explicitly tests whether added concentrate recovery is proportionate to the associated energy and solids burdens.

Table 1: Comparative screening of treatment functions; applicability depends on site-specific wastewater characterisation

Treatment function	Best-fit application	Potential contribution	Principal constraint
Source cascading	Suitable clean or lightly contaminated streams	Minimum new energy; low capital burden	Strict source–sink compatibility; scheduling
Coagulation / bio-treatment	Organic and colloidal wastewater	Reduces downstream organic fouling	Toxic shocks; dissolved salts remain

Treatment function	Best-fit application	Potential contribution	Principal constraint
UF / RO / polishing	Conditioned moderate-salinity water	Recovery for cooling or purified utility uses	Osmotic limit; concentrate remains
Electro-separation	Ion-selective or concentrated streams	Potential mineral partitioning	Specific-ion chemistry; electrical duty
Membrane distillation	Concentrated saline feeds and available heat	Additional distillate before crystallisation	Wetting, scaling and heat integration
Evaporation / crystallisation	Residual brine approaching salt saturation	Liquid elimination and solid recovery	Energy, corrosion, disposal and purity

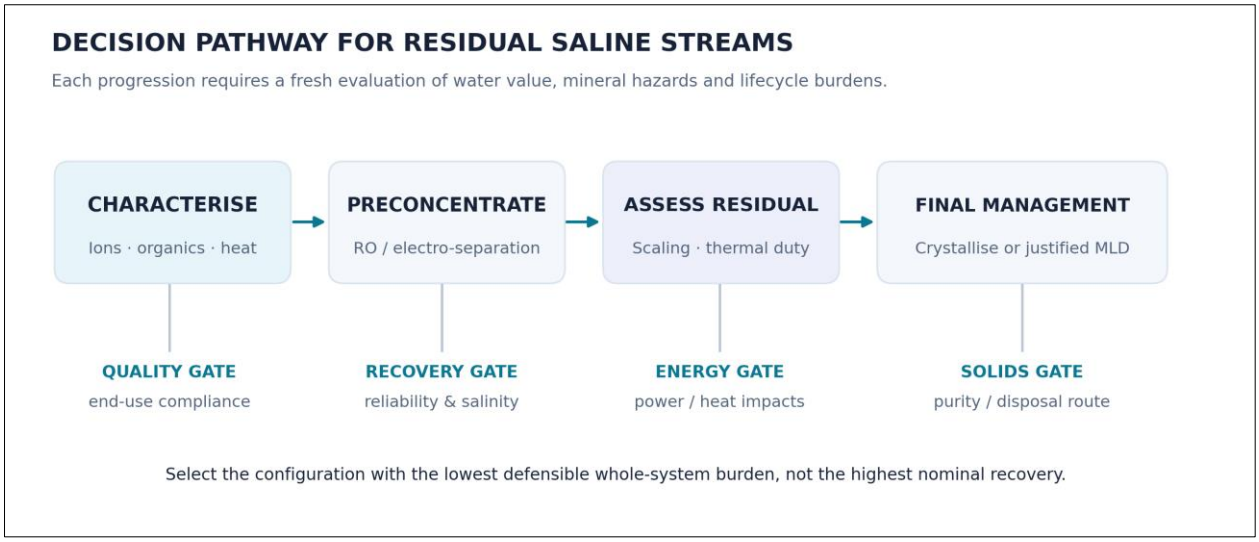


Figure 2: Quality, recovery, energy and solids decision gates for residual saline streams. Original conceptual synthesis

An illustrative mass balance clarifies the distinction between water reclamation and waste elimination. Consider a hypothetical facility sending 100 cubic metres of segregated wastewater to treatment during a defined accounting period. If 70 cubic metres meet a reuse specification and 30 remain as concentrate, measured recovery is 70%, provided storage changes and external additions are negligible. If a later concentration step returns another 20 cubic metres as condensate, aggregate recovery rises to 90%, but the remaining ten cubic metres still carry substantial dissolved material. Even if that last liquid fraction is converted to dry salts, the plant must report condensate quality, drying losses, entrained moisture and the ultimate disposition of all solids. These figures are an arithmetic illustration, not operational data or a prediction for a Saudi site. Their value lies in showing why claims based solely on a polished-water flow meter are incomplete.

Water-balance confidence also depends on instrumentation uncertainty. A small discrepancy across several large recirculating flows can conceal a meaningful loss of valuable make-up water. Pilot protocols should therefore document meter calibration, laboratory detection limits, sample frequency and reconciled measurement uncertainty. Financial evaluations need the same discipline: a saleable chemical salt must have a documented specification, a realistic off-take quantity and transport costs; otherwise revenue belongs in a sensitivity case rather than the base-case model. These safeguards make industrial water claims independently reviewable.

9. Economic and Environmental Tests

Decarbonisation should be tested against realistic operating schedules. A renewable electricity contract cannot eliminate the need for reliable heat and backup power during continuous chemical production. Review evidence on circular brine management shows that coupling treatment with low-carbon energy changes the environmental balance, but does not remove the need for integrated material recovery [26]. A robust sensitivity analysis should examine the marginal electricity emissions factor, possible steam curtailment, energy-storage losses and changing carbon prices. The correct comparison is not an optimistic design-day snapshot but the annual load profile required to maintain the same water supply and plant availability.

A credible project appraisal compares alternative service levels rather than merely capital expenditure on competing skids. Each option should deliver the same required volume and quality of

water, with accounted treatment of all residuals. Lifecycle cost incorporates equipment, chemicals, membranes, maintenance, energy, labour, salt transport, standby systems and eventual decommissioning. Techno-economic work on ZLD shows that reported unit costs can change considerably with system architecture and assumed by-product income [27]. Where heat is available as a process by-product, its opportunity cost should still be reported: waste heat used for evaporation may otherwise be recovered for productive heating or power generation.

Environmental evaluation likewise needs consistent boundaries. A ZLD train can reduce freshwater withdrawal and prevent saline discharge while simultaneously increasing electricity use or hazardous-solid generation. Brine studies identify resource recovery opportunities but stress that the recovered minerals' concentration and processing burden influence practical value [28]. Greenhouse-gas calculations should distinguish purchased electricity, direct fuel combustion and displaced supply. Comparisons based solely on the electrical consumption of RO and the thermal consumption of evaporation are invalid unless their energy types, heat recovery and functional output are made explicit.

Table 2 proposes decision metrics suitable for a Saudi pilot. It distinguishes process indicators, such as normalised membrane performance, from system outcomes, such as freshwater displacement and accountable solids removal. A plant could exceed its water-recovery target and still fail overall sustainability criteria if compressor energy or sludge production rose excessively. Operational availability is equally significant: an efficient treatment system that repeatedly forces a chemical plant to purchase emergency water does not improve resilience. The preferred design is therefore the configuration that protects production and reduces total lifecycle burdens within enforceable environmental limits.

Table 2: Proposed performance indicators for a site-qualified Saudi industrial water pilot; not reported field data

Indicator	Basis	Verification record	Interpretive safeguard
Withdrawal intensity	m^3 make-up per tonne of defined product	Production-normalised inlet meters	Freshwater displaced, not throughput recycled
Recovery and reuse	m^3 accepted product / m^3 wastewater fed	Reconciled feed, recycle and tank balances	Off-specification flow reported separately
Electric and thermal demand	kWh_e and kWh_{th} per m^3 fit-for-purpose water	Submetered utilities with heat accounting	No conversion of thermal to electric without method
Quality assurance	Application-specific limits and excursions	Laboratory, online and trend records	Compliance at actual destination
Residual integrity	kg solids, purity, water content and final fate	Weighbridge, speciation and manifests	Unsold material not credited as product
Operating resilience	Availability, cleaning and emergency make-up	Plant event logs and maintenance records	Failure-case resource and cost impacts

10. Implementation Priorities, Limitations and Research Needs

Mineral extraction is sometimes presented as a universal economic offset, although relevant ions may be dilute or embedded in difficult mixtures. Experimental investigations of selective resource recovery from zero-discharge desalination indicate that specific separation routes can recover valuable constituents, but their relevance depends on the incoming brine composition [29]. For Saudi chemical plants, a preliminary market assessment should therefore follow laboratory speciation and crystallisation testing rather than precede it. The assessment must distinguish revenue from a qualified product, avoided disposal fees and speculative value assigned to unverified recovered material. In particular, chemical reuse creates additional liabilities when impurities could enter sensitive manufacturing chains.

Implementation should be phased. Initially, plants should establish a three-month or production-cycle-sensitive baseline, reconcile all major utility flows and sample segregated wastewater during routine and abnormal operating states. Next, source–sink network optimisation and low-risk direct reuse can identify savings that do not depend on intensive desalination. Only then should pilot membrane and concentration tests be undertaken on representative blends and worst-case streams. Testing must include stop–start operation, cleaning transients, seasonal feed variation and credible failure responses.

For Saudi chemical clusters, promising research includes integration of renewable or otherwise curtailed heat with high-salinity concentration, scalable recovery of specification-grade salts, and secure data-sharing standards for industrial water exchanges. Work conducted at a Saudi research institution has examined a

membrane-distillation–crystalliser combination, offering a pertinent technical starting point rather than proof that every local plant can duplicate its results [30]. Another investigation of feed-specific industrial wastewater recovery strengthens the case for validating chemistry-dependent processes at demonstration scale [8]. Water scarcity alone does not determine the optimal configuration; market conditions, operating skills and treatment reliability remain decisive.

This review has limitations. Its literature base is intentionally focused, and the available studies employ heterogeneous scales, feed chemistries and costing conventions. The paper does not claim a complete census of all publications, perform an original field experiment or derive verified performance figures for Saudi facilities. Many published results concern seawater brine or municipal treatment, so transfer to solvent-bearing industrial wastewaters requires additional validation. Likewise, no national compliance guarantee can be inferred from a generic process diagram. Future multicentre pilot studies should disclose full mass balances, salt specifications, comparable energy boundaries and long-duration membrane performance to convert the proposed framework into site-qualified engineering guidance.

11. CONCLUSIONS

Sustainable industrial water management should begin with verified demand, segregated sources and quality-specific reuse rather than treating ZLD as the first design requirement. The reviewed literature supports a hierarchy in which direct cascading and rigorous accounting precede advanced membrane recovery, and thermal concentration is reserved for the residual water that simpler approaches cannot reclaim responsibly. Final salts require the same evidential scrutiny as treated water: composition, purity, destination and containment must be documented. Digital tools can improve foresight and operational control, but their authority depends on trustworthy instrumentation, physical constraints and clear human accountability. For Saudi chemical manufacturing, the strongest pathway is a modular, auditable strategy assessed against freshwater displacement, production reliability, lifecycle energy and residual hazards. ZLD becomes defensible when it demonstrably improves these combined outcomes, not when a nominal discharge target substitutes for whole-system engineering judgement. Future studies should publish comparable operating records across production cycles, including water quality excursions, unscheduled downtime, chemical dosing, membrane replacement and the final mass of recovered solids. Such evidence would enable fairer comparisons among technologies and make regional investment decisions more robust under changing industrial conditions.

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