Sustainable Industrial Water Management through Process Optimization, Wastewater Reuse, and Environmental Performance Improvement in Saudi Arabia.

Abstract

Industrial growth in Saudi Arabia intensifies competition for reliable water while raising questions about treatment energy, residual pollution and long-term resource security. This critical narrative review synthesises research published between 2020 and 2025 on three connected levers: process-level demand reduction, fit-for-purpose wastewater reuse and whole-system environmental performance. The review distinguishes evidence obtained from Saudi industrial operations from international studies whose methods require local validation. It examines water-network optimisation, source segregation, biological and membrane treatment, concentrate handling, monitoring and life-cycle assessment. Evidence indicates that water savings depend on matching stream quality with end-use requirements rather than maximising recovery at any cost. Industrial case studies support the technical feasibility of refinery water-network redesign, produced-water reclamation and reclaimed-water use in cooling systems, although transferable savings remain site-specific. A proposed management framework links baseline audits, multi-contaminant targeting, treatment selection, operational safeguards and transparent environmental accounting. The analysis identifies persistent gaps in variable-effluent datasets, contaminant risk, cross-plant infrastructure and comparative assessment of energy-intensive recovery routes. For Saudi industry, sustainable water management is best approached as a disciplined operational transition in which verified freshwater displacement, effluent quality, process reliability and environmental burden are evaluated together.

1. Introduction

Industrial water sustainability is a process-engineering problem before it becomes a question of selecting treatment equipment. Petrochemical complexes, refineries, power stations, metals producers and food manufacturers require water of different chemical and microbiological qualities; they also discharge streams with markedly different reuse potential. Treating all those streams to a single universal standard can waste energy, while combining them prematurely can destroy recovery opportunities. In Saudi Arabia, the issue is amplified by scarce perennial surface water, pressure on non-renewable groundwater and the energy requirements of desalinated supply. The national water-resource review by Alodah [1] provides essential climatic context, but an industrial approach must examine decisions made within the factory boundary and between neighbouring facilities.

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A shift towards circular operation does not mean that every litre should circulate indefinitely. In practice, conductivity, scaling potential, corrosivity, organic carbon, pathogens and specialised process contaminants constrain each reuse route. The relevant question is which water source can safely satisfy which demand after the least burdensome intervention. Ali and colleagues [2] describe the broader opportunity to convert treatment facilities into resource-recovery operations. Saudi field investigations offer a more specific basis: Ahmed and co-authors [3] evaluated produced-water desalination to displace utility-water demand, while Badruzzaman and colleagues [4] tested municipal reclaimed water for an industrial cooling application. These contributions demonstrate why supply substitution, process compatibility and operational protection belong in the same analytical framework.

A further challenge is the difference between a technically feasible reuse scheme and one that demonstrably improves environmental performance. Additional filtration, pumping, chemicals and residual disposal can offset the benefits of reduced abstraction. Infrastructure may also increase energy use through distant conveyance, duplicate treatment or conservative overdesign. Life-cycle studies emphasise the importance of comparing complete systems against explicit alternatives rather than assuming that recycling is automatically beneficial [6]. Without such boundaries, an apparently impressive recovery percentage can conceal higher emissions, concentrated pollution or prohibitive operational risk.

The aim of this review is to formulate an evidence-informed strategy for managing industrial water as an interconnected production resource in Saudi Arabia. Its specific objectives are to analyse methods of reducing avoidable process demand; evaluate appropriate wastewater reclamation and reuse pathways across contrasting industrial effluents; establish environmental and operational metrics for judging net improvement; and identify implementation priorities for Saudi industrial clusters. The central argument is that demand prevention should precede treatment intensification, and that successful reuse must be proven at the point of use rather than inferred from plant-outlet quality alone. The contribution is a practical, risk-aware synthesis rather than a new experiment or an unverified estimate of national savings.

2. Review methodology and analytical scope

A structured critical narrative approach was adopted because the research question spans process integration, treatment mechanisms, operational management and environmental accounting. The 2020–2025 publication window was applied to the cited studies. Evidence was located through targeted searches of peer-reviewed publication records and DOI-linked publisher pages using

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combinations of industrial water minimisation, water pinch, Saudi wastewater reuse, produced water, cooling-tower make-up, advanced treatment, zero liquid discharge, life-cycle assessment and digital monitoring. The attached Saudi water-resource review informed contextual interpretation, while additional industry-focused publications were assessed independently. Thirty distinct, DOI-identifiable studies were retained as the analytical bibliography.

Sources were selected for clear relevance to at least one review objective, identifiable publication details and a technical contribution that could be critically interpreted. Saudi case studies received priority when evaluating local feasibility. International research was included for methods and treatment trade-offs, but its numerical outcomes were not extrapolated to the Kingdom. Publications describing isolated laboratory performance were considered useful for mechanism appraisal, not proof of stable full-scale operation. Review papers supported technology comparisons, while engineering case studies informed the discussion of practical constraints. This is an interpretive evidence synthesis, not a statistically pooled comparison, and no database-wide retrieval counts or quantitative effect sizes are claimed.

Each study was examined against a common analytical matrix: water source and intended use, limiting contaminants, intervention, reported performance measure, system boundary, operational maturity and transferability. The synthesis separates three evidential levels. Direct Saudi observations establish local technical plausibility; overseas industrial studies illustrate methods that require site-specific testing; and conceptual frameworks suggest decision rules rather than measured benefits. The analysis also distinguishes savings in freshwater intake from reductions in wastewater discharge, because these quantities need not change proportionally. Environmental interpretations require attention to energy, chemicals, residual solids and contaminant fate. This evidence classification limits false precision and clarifies where field measurements remain indispensable. Evidence gaps were treated as limitations rather than filled with invented plant statistics. Studies involving different wastewater matrices, energy mixes and regulatory settings were compared qualitatively unless their system boundaries were sufficiently similar. This approach preserves useful engineering insight without implying an unsupported national average.

3. Reducing demand through process optimisation

A credible optimisation programme begins with an auditable water balance. Operators should map purchased and abstracted water, process additions, internal transfers, evaporation, product incorporation, blowdown, leaks and final discharges by operating mode. Meter placement must distinguish continuous baseload from batch peaks and shutdown cleaning. When nominal design

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values substitute for actual flow, opportunities are commonly misranked. Particular attention is required at cooling systems, steam and condensate networks, washing stations, utility headers and chemical dosing points. Source reduction includes repairing leaks, controlling wash duration, separating unnecessary once-through service, and returning clean condensate without contamination. These measures can avoid the treatment and conveyance burden of recycling water that should never have become wastewater.

Water pinch analysis formalises the matching of lower-quality sources with receiving processes whose contaminant limits are less restrictive. Esmaeeli and Sarrafzadeh [7] applied this reasoning to pulp-and-paper operations, while Hashemi and colleagues [8] examined refinery water demands using chemical oxygen demand and dissolved solids as limiting variables. The latter work reported substantial reductions in freshwater requirements under its case-specific assumptions; such percentages are not forecast values for Saudi refineries. More generally, single-contaminant calculations can produce misleading network targets when hardness, chlorides, silica, oil or biological activity also constrain operation. Multi-contaminant formulation is therefore essential when designing credible reuse linkages.

The optimisation problem is not simply to minimise intake. Chin, Klemeš and Wan Alwi [9] show how industrial exchange networks must account for several water-quality constraints and shared headers. Networks requiring many short-lived connections may be theoretically economical yet operationally fragile. The design should minimise unacceptable mixing, avoid reverse contamination, retain isolation valves and consider pressure compatibility. Nemati-Amirkolaii and colleagues [11] similarly frame industrial water targeting around contaminant accumulation and receiving-operation limits. A feasible solution should satisfy concentration constraints for each relevant pollutant, not just an aggregate water-quality score. Reliability, control simplicity and maintenance access are engineering objectives alongside freshwater savings.

Dynamic production complicates static targets. A wash-water stream available at night may not be useful to a process that demands it during daytime operation unless storage and quality control are provided. Inventory tanks, fluctuating product grades, summer evaporation and turnaround periods alter the optimum configuration. A multi-period model should therefore assess representative operating states and failure scenarios rather than rely on a single annual average. Water-quality classes can help planners handle heterogeneity; Chin and co-authors [10] combined classification techniques with integration analysis to identify regional recycling opportunities. Nevertheless,

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automated classifications must preserve transparent chemical thresholds and cannot replace testing for trace contaminants, scaling or biological risk.

Transferability depends on sector. Refinery operations may produce hydrocarbon-bearing streams requiring dedicated segregation, whereas textile applications can be limited by colour, salts and oxidants. Shabbir and colleagues [12] demonstrated multi-contaminant targeting in a textile setting, but a chemical manufacturing complex may require different constraints and stronger hazard barriers. Optimisation also needs an economic boundary: pipework, isolation equipment, pumping, downtime and treatment upgrades belong in total costs. The most robust sequence is to establish a credible baseline, remove avoidable demand, identify directly reusable streams, then add treatment only where remaining quality incompatibilities justify it. Figure 1 translates this sequence into a site-level operational architecture. A practical audit should identify apparent savings caused merely by changes in product mix. When output shifts from a water-intensive grade to a less demanding grade, aggregate intake may fall without any actual improvement in process efficiency. Reporting both production-normalised and absolute water flows helps prevent such misinterpretation. A robust network should also survive planned maintenance. Bypass capacity, isolation arrangements and staged commissioning may initially reduce calculated water efficiency, yet they prevent single-point treatment failures from interrupting production. Such resilience provisions belong in design appraisal instead of being dismissed as inefficiency.



Figure 1. Proposed sequence for process-led industrial water conservation and reuse (original conceptual synthesis).

4. Recovery, treatment and safe reuse

Reuse quality should be specified backwards from the receiving application. Cooling-tower make-up requires attention to scaling, corrosion, biofouling and aerosol-related microbial risk; boiler feed demands substantially tighter control of dissolved salts and silica; certain washing or construction operations tolerate less demanding specifications. A tertiary effluent may be suitable for one service

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but not another. Saudi evidence from Badruzzaman and colleagues [4] is especially pertinent: their industrial cooling study found that reclaimed municipal water could reduce consumption while effective disinfection and biocide management addressed measured biological hazards. The reported improvement concerned a particular facility and must not be treated as universal for all hot-climate systems.

Table 1. Illustrative fit-for-purpose reuse decisions; requirements must be confirmed against each site and applicable specifications.

Industrial application	Minimum decision basis	Main control / restriction
Cooling-water make-up	Hardness; chloride; biology; conductivity	Scale, corrosion, aerosol exposure; cycles of concentration
Boiler and steam services	Silica; conductivity; dissolved salts	Polishing and continuous verification; avoid carryover
Process washing / utility uses	Organics; solids; product compatibility	Prevent product contamination and unstable residues
Refinery / produced-water reuse	Oil, salinity, scaling ions, destination	Segregation, multistage treatment, residual management
Inter-plant water exchange	Multi-contaminant envelope; logistics	Shared interface limits, fallback and liability

Where industrial wastewaters contain oil, solvents, heavy metals or variable salinity, source-specific pretreatment protects downstream assets and reuse quality. Equalisation absorbs fluctuations; oil separation and coagulation can reduce fouling precursors; biological processes remove biodegradable organics; membranes provide additional solids or salt separation. The order is consequential. Applying reverse osmosis directly to inadequately treated effluent can increase pressure losses and cleaning frequency, while excessive pretreatment can consume resources without proportional benefit. Al-Asheh and colleagues [19] review membrane-bioreactor fundamentals and the constraints imposed by membrane fouling. A sound treatment train is therefore selected through water characterisation and achievable end-use quality, not technology prestige.

Anaerobic membrane treatment adds the possibility of recovering energy from organic matter, but published assessments caution against overselling this capability. Robles and colleagues [13]

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discuss resource recovery pathways, and Aslam and co-authors [14] identify salinity, inhibitory compounds and membrane stability among practical limitations. Huang, Jeffrey and Pidou [15] specifically show that untreated anaerobic-membrane effluent cannot routinely satisfy all non-potable reuse requirements without polishing. Mahmood and colleagues [16] further demonstrate the relevance of configuration and energy demand. For Saudi facilities, high wastewater temperature may support biological kinetics, but inhibitory chemicals and salt accumulation must be assessed before an anaerobic route is selected.

Hybrid separation options may become relevant where process water carries high dissolved solids or difficult organic compounds. Kharraz and co-authors [17] discuss membrane-distillation bioreactors and their water-recovery potential while identifying wetting, low flux and volatility limitations. Daud and colleagues [18] examine microbial electrochemical combinations, but emerging configurations should not be interpreted as validated replacement systems for mature industrial treatment. When oxidation is needed, contaminant destruction must be evaluated through actual toxicity reduction and transformation products. Mukherjee and colleagues [25] review advanced oxidation routes, and Mahbub and Duke [26] caution that radical generation, deployment mode and scalability affect industrial viability. Technology selection should follow contaminant-specific pilot work and realistic utility accounting.

For Saudi oil operations, Ahmed and colleagues [3] document field-oriented produced-water recovery directed towards low-salinity process and utility applications. Such programmes may conserve groundwater, but produced-water chemistry can vary with reservoir and production practices. Treatment must consider hydrocarbons, barium, strontium, scaling tendency and residual disposal before design throughput is asserted. Recovered water should undergo an acceptance protocol that measures quality at delivery and during stressed operating states. Reliable reuse requires automatic diversion of off-specification water, separate storage where necessary, and an identified fallback supply. This approach makes reuse a controlled industrial service rather than an uncontrolled connection between waste and production systems. Chemical compatibility should be tested against the receiving system rather than judged solely by generic discharge limits. Even low concentrations of silica, chloride or surfactants may become consequential after evaporation or repeated cycling. Materials selection, microbial controls and cleaning procedures must respond to this cumulative exposure. Water safety plans should include explicit responses to power failures, chemical overfeed and membrane integrity loss. Monitoring alarms without identified actions provide limited protection. Each critical alarm requires a defined diversion route, response owner and documented procedure for returning to service after confirming recovered-water quality.

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5. Residual management and environmental performance

Membrane recovery does not eliminate pollution; it transfers much of the rejected material into a smaller, more concentrated stream. The concentrate may contain salts, organic micropollutants, metals and cleaning residues that complicate discharge. Zero-liquid-discharge systems offer a possible solution where regulatory and environmental conditions justify their deployment. Date and colleagues [20] review available reclamation approaches, while Abdelfattah and El-Shamy [21] survey more intensive zero-discharge configurations. A maximum-recovery target is not automatically environmentally optimal. Evaporation, crystallisation, solid waste conditioning and corrosion-resistant construction can create burdens that exceed the benefit of incremental water recovery.

Brine management should be evaluated according to pollutant mass, not only volumetric discharge. A reduction in liquid volume can coexist with unchanged salt loading or with greater toxicity of the remaining fraction. Desulphurisation wastewater studies highlight the difficult chemistry and treatment combinations associated with concentrated industrial residues [22]. Li and colleagues [23] compare alternative concentrate-handling pathways through integrated technical, environmental and economic appraisal. Yao and co-authors [24] extend such appraisal to cold-rolling wastewater. These studies support conditional decision-making: concentrate reuse, recoverable material extraction, permitted discharge and thermal treatment should be compared within the same boundary. No residual-management pathway should be labelled sustainable until its destination and lifecycle impacts are documented.

Life-cycle assessment adds information that conventional cost and effluent testing cannot capture. An appropriate functional unit may be one cubic metre of verified fit-for-purpose water delivered to the user, accompanied by a fixed quantity of industrial output where production intensity changes. The system boundary should include replacement water avoided, pretreatment, electricity, chemical inputs, pipelines, membrane replacement, sludge management and final residual disposition. Çapa and colleagues [6] demonstrate that industrial water recovery can entail environmental and financial trade-offs. Comparing only treatment-unit electricity while omitting avoided desalination or inland pumping can bias results; equally, assigning the entire freshwater benefit without tracking downstream losses overstates reuse value.

Water quality compliance and broader environmental improvement require distinct metrics. Quality compliance establishes whether a discharge or reclaimed stream meets a defined threshold. Environmental performance measures the wider consequences of the chosen route, including

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greenhouse-gas emissions, nutrient and chemical releases, freshwater stress, sludge generation and acute process hazards. For industrial clusters, accounting should avoid double-countinga water transfer as a saving at both the donor and receiving plants. The same physical litre may be reported as recovered effluent and displaced freshwater, but these are related indicators rather than independent resource gains. Boundary definitions, reference scenarios and allocation methods must be disclosed before companies compare performance or claim aggregate benefits.

Environmental performance improvement is also an operational matter. A treatment plant designed for a theoretically low energy value may consume substantially more electricity under variable salinity, membrane fouling and repeated cleaning. The practical indicators should therefore be measured over representative annual conditions, with downtime and off-specification bypass recorded explicitly. Water savings should be expressed both as absolute freshwater displacement and as intensity relative to a stable production denominator. Energy intensity, contaminant mass discharged and residual-treatment burden should appear alongside recovery percentage. Table 2 provides an indicator set designed to prevent a single favourable metric from dominating decisions. These comparisons enable site managers to distinguish genuine improvement from burden shifting. The location of the replacement source can materially change the environmental comparison. Displacing locally available industrial condensate is different from displacing energy-intensive transported desalinated water. The avoided-source scenario must therefore specify both where water would otherwise originate and the physical infrastructure through which it would travel. When chemical oxygen demand is used as a headline indicator, interpretation requires care: it captures aggregate oxidisable material rather than the hazardous character of particular compounds. Trace metals, persistent organics and biological risk need additional measurements whenever receiving environments or industrial processes are sensitive.

Table 2. Proposed monitoring indicators for whole-system environmental and operational assessment.

Dimension	Primary indicator	Verification requirement
Resource protection	Net freshwater intake and intensity	Metered baseline; production-normalised comparison
Circular delivery	Fit-for-purpose reuse accepted by user	Volume and quality measured at end use
Treatment energy	kWh per cubic metre of delivered reuse	Inclusive of pumping, cleaning and pretreatment

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Environmental load	Pollutant mass; greenhouse-gas inventory	Defined boundary, residual disposal and avoided supply
Reliability and safety	Off-specification episodes; interruption hours	Auditable isolation, sampling and corrective actions

6. Proposed integrated management framework

The synthesis suggests a five-stage implementation framework, shown in Figure 2. The first stage establishes governance and a transparent evidence baseline. Plants document source types, demand profiles, quality requirements, metering confidence, reuse history and applicable restrictions. They also identify the users accountable for water quality and process reliability. The second stage applies engineering prevention: leak correction, condensate return, process controls, cooling-cycle adjustments and multi-contaminant targeting. Savings achieved without complex new infrastructure should be verified before designating investment for high-grade treatment. This sequence limits unnecessary capital expenditure while producing practical operating data for more demanding schemes.

The third stage matches effluent streams with suitable demands through an explicit contaminant matrix. For each proposed transfer, design teams evaluate average and worst-case concentrations, variability, transport distance, storage residence time and fail-safe arrangements. Reuse pathways are ranked by net displaced freshwater per unit of added energy and by implementation risk, rather than recovery alone. A shared industrial header may provide economies of scale but introduce dependency and accountability questions. Cross-company contracts must specify who controls quality at the interface, who pays when a stream is diverted, and how process contamination will be isolated before it propagates through the network.

The fourth stage selects and tests treatment only for the unresolved quality gap. Pilot studies should cover representative operational campaigns, cleaning cycles, shock loads and seasonal conditions. Acceptance criteria need to specify contaminant concentrations, stable permeate flow, chemical consumption, residual mass and protection of the receiving asset. A treatment pilot that achieves a high removal percentage but fails during transient loads should not be classified as ready for continuous industrial duty. Likewise, a reuse design should include buffer storage and fallback supplies where interrupted water delivery could create production or safety consequences. The cost of reliability forms part of the decision, even when it is absent from a laboratory comparison.

The fifth stage independently verifies benefits after commissioning. Monitoring infrastructure can support timely response to deviations, but instrumentation should be selected for decision value.

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Nishan and colleagues [27]investigate digital wastewater sensing, while Daneshgar and co-authors [28] report a full-scale facility model linked to operational data. Wang and colleagues [29] analyse digital-twin architectures, and Shah and co-authors [30] explore prediction for ozone-related treatment performance. These studies indicate useful tools; they do not justify substituting model outputs for calibrated laboratory measurements. Sensor drift, missing observations, cybersecurity, explainability and operator override require systematic controls.

The framework is intentionally iterative. A changed feedstock, production campaign or electricity mix can alter both optimal reuse and environmental impact. Annual review should revisit contaminant limits, energy baselines, capital performance, microbiological controls and the destination of residual solids. Senior management needs dashboards that display uncertainty rather than polished but misleading single-point efficiencies. Where financial and environmental targets conflict, alternatives should be evaluated through explicit trade-offs, not concealed weighting. The proposed structure is a decision-support contribution derived from the literature, not a validated model of any specific Saudi complex. Its credibility ultimately depends on measured local trials and transparent reporting. Where network storage is proposed, designers should evaluate residence-time distributions and segregation during abnormal operation. Storage provides flexibility, but it can also promote biological regrowth, quality drift and delayed detection of contamination. Routine sampling points should therefore cover both inlet and outlet conditions. A useful management dashboard should report absolute abstraction, verified reuse delivery, environmental loads and water-related production interruptions together. Narrowly optimising any one measure risks unintended consequences elsewhere. Showing the joint trajectory helps operators identify whether improved recovery is accompanied by stable or worsening environmental performance.

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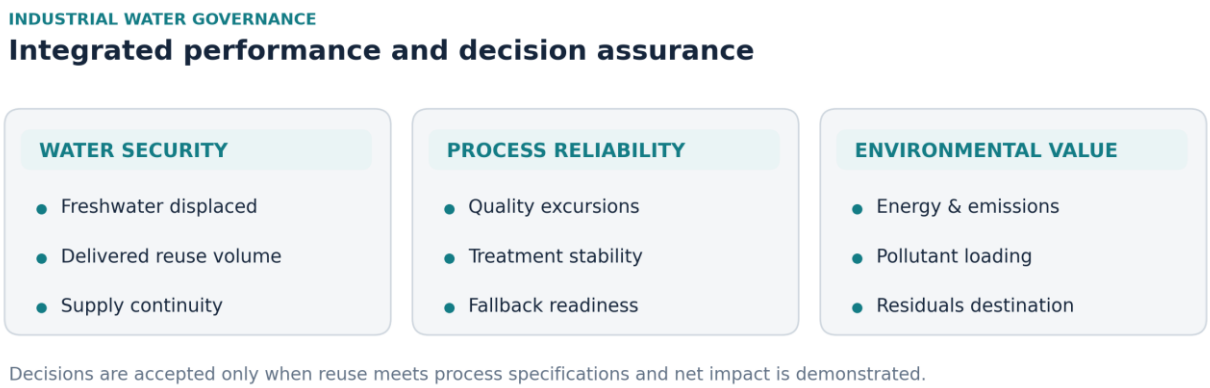


Figure 2. Three linked dimensions used to verify industrial water-management performance (original conceptual synthesis).

7. Implications for Saudi industrial development

Saudi industrial sectors present contrasting implementation pathways. Refinery and petrochemical assets may prioritise oily-water segregation, treatment of process condensates and substitution of treated effluent in utility services. Mining and metals facilities must consider solids, metal toxicity and saline concentrate disposal. Food-manufacturing operations often benefit first from improved cleaning procedures and water-quality segregation. Energy-intensive utilities may obtain value from optimised cooling cycles and reclaimed make-up. Industrial symbiosis could enable exchange between neighbouring plants, particularly where water-rich sources and lower-grade demands coexist, but pipe corridors, contractual allocation and process safety can be decisive. General recommendations must therefore be translated into sector-specific contaminant specifications and operating envelopes.

A Saudi implementation strategy should start with demonstration sites that already maintain credible metering and effluent records. Baseline periods must encompass seasonal temperature variation and meaningful shifts in throughput. Projects should be independently evaluated against a documented business-as-usual counterfactual; energy and water volumes should be normalised for production when appropriate. Reuse programmes should not claim net national water savings by extrapolating an individual demonstration percentage across unrelated sectors. Alhajri and colleagues [5] assess the development of treatment and reuse infrastructure nationally, but industrial adoption still requires evidence concerning local water prices, quality requirements, incentives and operational competence. Scaling depends on these institutional conditions as well as treatment performance.

The technical research agenda should prioritise openly documented, multi-season operating datasets; comparison of direct reuse with regeneration and recycling; and robust assessment of salinity accumulation in repeated water loops. Additional priorities include trace-organic monitoring, microbiological risk in aerosol-forming equipment, predictive control under sensor drift, and life-cycle evaluation of concentrate-management alternatives. These questions are particularly significant where power generation, petrochemicals and desalination intersect. Public reporting could establish consistent definitions for freshwater displacement, reuse reliability and disposal quality while protecting commercially sensitive process details. Future studies should compare interventions within the same site and production conditions whenever practical, reducing biases introduced by heterogeneous feedwater and inconsistent environmental boundaries.

Governance matters because the strongest engineering solution can still fail when duties are fragmented. Production teams seek continuity, utility departments manage treatment equipment,

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environmental personnel oversee discharge limits, and procurement teams evaluate costs. A project charter should define common performance objectives, an agreed method for verifying savings and authority to isolate poor-quality recycled water. Operator training must cover unfamiliar chemical hazards and not merely routine monitoring screens. Independent auditing should check whether off-specification episodes are recorded and whether water-quality changes harm receiving equipment. The organisational lesson is that circular industrial water management requires shared accountability for both reused water and the residues it creates. Independent evaluation also requires clear reporting of uncertainty in flow meters and laboratory measurements. Small apparent changes in consumption may fall within instrument error, especially when several unmeasured recirculation loops are combined. A savings claim should survive reasonable error bounds before being used to justify further investment. Future policy evaluations should distinguish an increase in treatment capacity from an increase in actual beneficial reuse. Installed infrastructure alone does not show that quality is accepted, that transfer networks operate reliably or that freshwater supplies are displaced. Delivered and used volumes are the relevant operational evidence. Comparative research would benefit from common reporting templates that record feedwater chemistry, pretreatment train, operating pressure, membrane age, recovery fraction, product quality and concentrate destination. Such consistent records would permit more defensible inter-site comparisons than selective reporting of best-day treatment efficiencies.

Procurement and project appraisal also require a consistent distinction between technical potential and delivered benefit. Preliminary network calculations often represent ideal mixing and uninterrupted access to wastewater streams. Real facilities face minimum tank levels, imperfect hydraulic separation, delayed laboratory results, equipment ageing and periodic cleaning. A candidate project should therefore progress through several decision gates. At feasibility stage, the source water must be shown to exist with adequate volume and predictable quality. At pilot stage, the proposed treatment or direct transfer must demonstrate compliance under representative disturbance conditions. At commissioning, instruments, diversion valves and operators must prove that abnormal water cannot enter a sensitive process. During routine operation, the measured freshwater reduction must be reconciled with plant production, unexpected downtime and actual utility consumption. Performance reporting should specify the denominator and date range rather than mixing design capacity with operating output. The sequence is especially important for industrial clusters, where one facility's changed production schedule can make another facility's reuse source unavailable. Contracts should define minimum delivery, acceptable contamination envelopes and liability during disruption, but should not substitute legal documentation for

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protective engineering. Environmental assessment similarly needs a counterfactual reflecting the local supply that is truly displaced, rather than an assumed generic freshwater source. The calculation should disclose whether electricity comes from a fixed grid mix, onsite generation or variable supply; whether treatment residuals are transported; and whether replacement membranes and chemicals are accounted for. These distinctions determine whether apparent water savings correspond to a genuine environmental gain. Independent post-commissioning review can then identify cases where a simpler process change performs better than an elaborate recovery plant. Building evidence in this disciplined manner supports practical investment decisions while retaining the central public objective of reducing pressure on scarce Saudi water resources. For these reasons, performance guarantees should specify verified delivery volumes, agreed quality limits, documented fallback arrangements, transparent energy accounting, and an independent operational testing period across seasonal operating conditions.

8. Conclusions

Sustainable industrial water management in Saudi Arabia requires coordinated reduction of demand, selective recovery of wastewater and rigorous evaluation of environmental results. The reviewed studies support water-network optimisation, source-specific treatment and carefully controlled reuse, but they do not establish a universal recovery percentage or single superior technology for every facility. The strongest practical evidence comes from programmes that connect water-quality monitoring with the needs of actual industrial users. Meanwhile, whole-system appraisal demonstrates why reduced freshwater demand must be considered together with energy, chemicals, residual pollution and operational risk. The proposed framework places verified process efficiency before high-intensity treatment and links technology selection to enforceable end-use requirements. Its application should proceed through measured pilots, transparent baselines, contamination safeguards and periodic reassessment. Further comparative trials across Saudi industrial sectors are necessary before broad claims of performance, costs or national-scale benefits can be substantiated.

Keywords: industrial water management; process optimisation; water pinch analysis; wastewater reuse; resource recovery; life-cycle assessment; Saudi Arabia.

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