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REVERSE OSMOSIS (RO) CONCENTRATE MANAGEMENT: A NARRATIVE REVIEW

Narrative Review

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ABSTRACT

Background: The rapid global expansion of reverse osmosis (RO) desalination, driven by urbanization, climate change, and escalating water scarcity, has led to the generation of large volumes of highly saline concentrate (brine). Management of this byproduct remains a critical environmental and regulatory challenge, as conventional disposal practices are associated with ecological degradation, soil salinization, and marine toxicity. At the same time, growing pressure on freshwater resources has prompted renewed interest in viewing RO concentrate as a potential resource rather than solely as waste.

Objective: This narrative review aims to synthesize current evidence on the composition, environmental risks, regulatory context, and emerging opportunities for the sustainable reuse of RO concentrate, with particular emphasis on its integration into circular water and agricultural systems.

Main Discussion Points: The review discusses the physicochemical characteristics of RO concentrate, highlighting its high total dissolved solids and dominance of sodium and chloride ions. Key disposal pathways and their environmental implications are examined alongside evolving regulatory approaches. The review further explores reuse strategies, especially in agriculture, including dilution-based irrigation, halophyte cultivation, hydroponics, and soil amendment practices. Critical soil–water quality parameters such as electrical conductivity, sodium adsorption ratio, and residual sodium carbonate are emphasized as determinants of safe and effective reuse.

Conclusion: The evidence suggests that, under controlled and site-specific conditions, RO concentrate can be repurposed to support water-efficient and nutrient-aware agricultural practices. However, long-term sustainability depends on rigorous monitoring, interdisciplinary collaboration, and strengthened regulatory frameworks. Reframing RO concentrate as a recoverable resource offers a promising pathway toward resilient and circular water management.

Keywords: Agricultural water reuse, Brine management, Circular water systems, Reverse osmosis concentrate, Salinity and sodicity, Water-scarce regions.

INTRODUCTION

Urbanisation is progressing at an unprecedented pace worldwide, fundamentally reshaping patterns of resource demand and environmental stress. The global urban population increased from 0.8 billion (29.6%) in 1950 to 4.4 billion (56.2%) in 2020 and is projected to reach 6.7 billion, representing nearly 68.4% of the world's population by 2050. This rapid demographic transition has placed immense pressure on urban water systems, where demand increasingly exceeds supply, directly influencing public health, environmental quality, and socioeconomic development (1-3). At present, a substantial proportion of metropolitan populations already experience water scarcity, and this challenge is expected to intensify as urban water demand for domestic and industrial uses rises by an estimated 50–80% over the next three decades due to population growth, urban expansion, and economic development (4,5). Climate change further compounds urban water insecurity by altering the timing, intensity, and spatial distribution of water availability, thereby disrupting established hydrological cycles (2,6). Consequently, future projections consistently indicate a marked escalation in urban water scarcity, with profound implications for achieving the United Nations Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation) and SDG 11 (Sustainable Cities and Communities) (7,8). Beyond urban settings, agriculture remains the dominant consumer of freshwater, accounting for approximately 70% of global withdrawals to irrigate nearly one-quarter of the world's arable land (9). Growing competition among urban, industrial, and agricultural sectors, combined with climate variability, is increasingly constraining farmers' access to reliable water supplies, threatening food security and livelihoods (10,11).

Freshwater availability is a critical abiotic determinant of ecosystem integrity and human survival, underpinning agriculture, industry, and public health (12,13). Although the natural water cycle plays a central role in maintaining freshwater quality, excessive abstraction and pollution can overwhelm its regenerative capacity. Anthropogenic pressures and climate-induced alterations to the global water cycle have accelerated the degradation and depletion of freshwater resources, adversely affecting human well-being and ecological resilience across many regions (10). Current consumption trends increasingly challenge the conventional perception of freshwater as a renewable resource, particularly in water-stressed regions facing rapid urbanisation and intensified agricultural demand (10-12). Unsustainable groundwater abstraction alone affects more than one-quarter of the global population and supports over 40% of agricultural production, underscoring the scale of the problem. The human consequences of water scarcity are already stark. More than 700 million people lack access to safe drinking water, while over 40% of the global population experiences water stress (13). Inadequate wastewater management exacerbates these challenges, with nearly half of all human-generated wastewater discharged untreated into rivers or oceans, posing serious risks to environmental and public health. Water insecurity has been linked to desertification, forced migration, food insecurity, disease burden, and regional conflicts. Transboundary river systems illustrate these tensions, as exemplified by large-scale irrigation enabled by the Atatürk Dam on the Euphrates River, which has contributed to reduced water quantity and quality downstream in Iraq and northeastern Syria (14).

In response to escalating freshwater scarcity, desalination has emerged as a key technological strategy to augment water supplies, particularly in arid and coastal regions. Desalination can be applied to seawater, brackish water, and wastewater, and global installed capacity reached approximately 115 million m^3 day^{-1} (about 42 billion m^3 $year^{-1}$) by 2020 (11). Despite its growing importance, desalination remains associated with significant challenges, including high energy demand, elevated costs, and environmental concerns related to concentrate disposal (7). Reverse osmosis (RO) is the dominant desalination technology, relying on spiral-wound polyamide membranes that effectively reject dissolved salts and impurities while producing potable water (8). Commercial seawater RO systems typically operate at recovery rates of around 45%, with higher recoveries increasing brine salinity, osmotic pressure, and energy requirements (9). The reject stream from RO processes, commonly referred to as brine, is characterised by high salinity and electrical conductivity. Reported total dissolved solids (TDS) range from 10,000 to 70,000 mg L^{-1}, with conductivities of 25,000–90,000 µS cm^{-1}, depending on the source water and operating conditions. In seawater-derived brine, sodium and chloride dominate the ionic composition, together accounting for approximately 50 g L^{-1} of the total dissolved solids. Brines generated from municipal wastewater or brackish sources typically exhibit lower TDS (3–8 g L^{-1}) but still contain high concentrations of Na^+, Cl^-, SO_4^{2-}, and HCO_3^-, along with trace metals and organic compounds. Because RO membranes reject more than 98% of dissolved ions, the chemistry of the feed water largely determines brine composition, and increases in recovery rates further concentrate salts and scaling precursors (14-16). Globally, brine generation volumes are substantial, with estimates ranging from 140 million to over 50 billion m^3 day^{-1}, approximately 70% of which originates from the Middle East and North Africa. Although region-specific data remain limited, arid coastal regions dependent on seawater RO clearly generate the largest brine volumes, while inland brackish groundwater and wastewater reuse facilities contribute significantly in water-stressed basins. Regulatory frameworks governing brine disposal vary widely and typically focus on salinity-related parameters rather than comprehensive brine management, highlighting a critical gap in sustainable desalination practices. Against this backdrop, the central research question guiding the present study is how reverse osmosis brine can be managed more sustainably to mitigate environmental risks while supporting water security in an era of accelerating urbanisation, agricultural demand, and climate change. The objective of this research is to critically evaluate the characteristics, drivers, and implications of RO brine generation and to identify evidence-based strategies that enable safer disposal, resource recovery, or beneficial reuse, thereby contributing to resilient and sustainable water management systems.

United States

Regulation of reverse osmosis (RO) brine discharge in the United States is characterised by a decentralised, site-specific approach rather than uniform national numeric limits. The US Environmental Protection Agency does not prescribe federal salinity caps for industrial or desalination brine; instead, discharge is regulated through National Pollutant Discharge Elimination System (NPDES) permits that emphasise compliance with local water quality objectives and toxicity-based thresholds (11). This framework reflects an ecological risk-based philosophy, where acute and chronic toxicity to aquatic organisms is prioritised over fixed limits for total dissolved solids (TDS) or chloride. For instance, the Carlsbad seawater desalination plant permit specifies a No Observed Effect Concentration (NOEC) of 42 ppt salinity, a Lowest Observed Effect Concentration (LOEC) of 44 ppt, and a short-term toxicity limit of 46 ppt, illustrating how biological response data guide regulatory decisions rather than absolute salinity values (12). While this adaptive approach allows flexibility across diverse receiving environments, it also creates variability and uncertainty in brine management practices, particularly as desalination capacity expands in coastal regions.

World Health Organization

The World Health Organization adopts a fundamentally different perspective, focusing primarily on drinking water quality and public health protection rather than environmental discharge standards. WHO guidelines address aesthetic acceptability thresholds, such as the development of a salty taste when chloride concentrations exceed approximately 250 mg L^{-1}, and establish health-based limits for potentially toxic constituents, including heavy metals (12). However, the WHO does not provide explicit guidance on desalination brine discharge into aquatic environments. This absence reflects the organisation's mandate but also highlights a critical gap at the global level, where internationally harmonised benchmarks for brine disposal are lacking despite the transboundary nature of marine and freshwater ecosystems.

Pakistan (NEQS)

In Pakistan, brine disposal is regulated under the National Environmental Quality Standards (NEQS), which permit effluent discharges to inland surface waters with TDS up to 3,500 mg L^{-1} and chloride up to 1,000 mg L^{-1}, often contingent upon significant dilution ratios, commonly around 1:10. These limits are far exceeded by typical RO brines, which frequently contain 10,000–70,000 mg L^{-1} TDS, rendering direct compliance impractical without extensive dilution or treatment. Consequently, inland desalination and RO-based water reuse facilities face substantial operational and economic challenges in meeting NEQS requirements. This regulatory mismatch underscores the tension between growing reliance on RO technologies for water security and the absence of brine-specific standards tailored to local hydrogeological and ecological conditions.

Morocco

Morocco's rapid expansion of coastal desalination capacity has brought brine management into sharper regulatory focus. National discourse increasingly recognises the "critical need" for both effluent standards at discharge points and ambient standards in receiving environments to prevent localised salinity accumulation and ecological degradation (13). However, despite this recognition, Morocco has yet to define explicit numeric limits for salinity or brine-related constituents. This situation mirrors that of many emerging desalination-dependent countries, where policy development has not kept pace with technological deployment, leaving brine management largely guided by project-level environmental impact assessments rather than enforceable national criteria.

Table 1: Represents phytochemistry of RO concentrate (brine) of different sources

RO water	TDS	EC (µS/cm)	Na^+	Cl^–	Ca^2+	Mg^2+	SO_4^2–	Results	References
Seawater (SWRO brine)	~50,000 mg/L	~80,000 µS/cm	~20,000	~35,000	~800	~2,600	~5,000	High-salinity; NaCl-dominant (similar to seawater proportions).	(Sirota, et al. 2024)
Brackish water (BWRO)	~10,000 mg/L	~15,000 µS/cm	~3,000	~7,000	~500	~300	~1,000	Moderate salinity; variable composition (depends on aquifer). Typical in inland RO plants.	(Sirota et al., 2024)
Municipal reuse water	3,000–8,000	-	300–3,000	300–4,000	100–500	50–300	200–1,000	Lower salinity; includes nutrients and organic solutes. Values from US reuse plants.	(Parsons et al., 2010)
Textile industry RO reject	~58,600	-	~20,600	~14,400	-	-	~23,600	Example high-salt brine (NaCl/Na_2SO_4 feed). Phase-1 pilot: 58.6 g/L TDS (0.68:1 NaCl:Na_2SO_4).	

DIRECT DISCHARGE

Direct discharge remains the most widely applied brine disposal strategy worldwide due to its relative simplicity and cost-effectiveness. In coastal settings, RO brine is commonly released into marine environments, while inland facilities may rely on surface discharge, deep-well injection, or evaporation ponds (14,15). Although economically attractive, direct discharge poses well-documented physicochemical and biological risks. High salinity, elevated temperature, and dense ionic loads can reduce dissolved oxygen levels, disrupt osmotic balance in aquatic organisms, and alter benthic community structure (10). Brine constituents such as chloride, sulphide, and residual treatment chemicals further exacerbate toxicity risks when insufficiently diluted. Empirical evidence suggests that approximately 1 m^3 of brine is generated per cubic metre of desalinated water, and environmental release remains the dominant disposal route globally (16). Despite technological advances in desalination efficiency, brine management has lagged behind, increasingly being recognised as both an environmental liability and a cost-intensive challenge (17).

Reject Brine Management and Applications

Growing awareness of the limitations of direct discharge has driven interest in alternative reject brine management strategies that align with principles of sustainability and circular economy. Recent literature emphasises integrated approaches that combine dilution, advanced treatment, and resource recovery to mitigate long-term environmental impacts (18). Conceptual frameworks increasingly view brine not solely as waste but as a secondary resource containing salts, minerals, and energy potential. Valorisation pathways include mineral recovery, aquaculture, algal cultivation, and energy generation, although many remain at pilot or demonstration scale. Comparative analyses highlight that while such approaches can reduce environmental burdens, their feasibility is highly context-dependent, influenced by brine composition, scale of operation, regulatory acceptance, and economic viability. Persistent gaps remain regarding long-term ecological safety, scalability, and standardised monitoring protocols, underscoring the need for site-specific assessments and robust life-cycle analyses.

The RO concentrate can be reused in agriculture

Agricultural reuse of RO concentrate has emerged as a particularly compelling yet controversial application. Brine streams often contain substantial concentrations of macronutrients such as calcium, magnesium, and potassium, which can partially substitute synthetic fertilisers, especially in hydroponic or soilless systems when appropriately diluted to safe electrical conductivity levels (19). International studies demonstrate that halophytic and salt-tolerant crops, including *Salicornia bigelovii*, *Atriplex halimus*, and *Crithmum maritimum*, can produce edible biomass, fodder, or biofuel feedstock under brine irrigation regimes (19,20). Field and modelling studies further suggest that blended or rotational use of saline and freshwater irrigation can sustain yields of cereals and horticultural crops in arid regions, albeit with careful management of salinity thresholds (18,21).

However, the literature consistently cautions against unregulated application. Elevated electrical conductivity and sodium adsorption ratio (SAR) are strongly associated with soil salinisation, sodicity, structural degradation, and long-term yield decline when brine is applied without dilution or leaching (22,23). Meta-analyses indicate an average reduction of approximately 17% in crop productivity under saline irrigation compared with freshwater, with substantial variability among crops and management practices (24). Heavy metal accumulation and nutrient imbalances further complicate reuse, particularly where brine originates from mixed urban–industrial effluents (25). Conversely, controlled studies report that with appropriate blending, soil amendments such as gypsum, organic matter addition, and continuous monitoring of soil EC, SAR, and crop quality, adverse impacts can be mitigated and brine reuse integrated safely into agricultural systems (26).

Overall, the thematic synthesis indicates that while regulatory approaches, disposal practices, and reuse strategies for RO brine vary widely across regions, a common challenge persists: balancing water security benefits against environmental and public health risks. The evidence highlights the absence of harmonised discharge standards, the dominance of direct discharge despite known impacts, and the growing but cautiously optimistic body of research on agricultural and resource-oriented reuse. These findings collectively point to the need for integrated, site-specific frameworks that combine regulatory clarity, technological innovation, and long-term monitoring to enable sustainable brine management.

Table 2: Overview of literature on the use of RO concentrate or saline water to irrigate the soil (2019–2025).

No.	Type of water	System of crops	Technique	Location	Duration	Results	References
1	Waste brine (high salinity)	Hydroponics / halophytes	Field sampling	Tenerife, Spain (multi-site sampling)	2019-2020	Reject brine can be a source of minerals for hydroponics; crop selection (halophytes/hydroponic species) and blending are important; hydroponic conversion has demonstrated economic promise.	Jiménez-Arias et al., 2022

No.	Type of water	System of crops	Technique	Location	Duration	Results	References
2	ROC characteristics reviewed	Various	Review	Global review	-	The integration of constructed wetlands, dilution (blending) strategies, and advanced treatment approaches such as advanced oxidation processes and membrane-hybrid systems facilitates the safe reuse of reverse-osmosis concentrate, provided that rigorous monitoring of ionic composition and strict control of residual-sodium-carbonate (RSC) and sodium-adsorption-ratio (SAR) are maintained	Scholes et al., 2021
3	Desalinated brine	Various (algae, aquaculture, halophytes)	Review	Global review	-	Reverse osmosis concentrate can be valorized through a number of methods, such as algal cultivation, aquaculture applications, and the recovery of valuable minerals, while highlighting the possibility of soil salinization and stressing the necessity of pilot-scale testing to evaluate viability and environmental safety.	Lee et al., 2024
4	ECiw = 1.3–14.1 $dS \cdot m^{-1}$ (treatments)	Winter wheat–summer maize rotation	Field experiment	China	Multi-year (since 2006 treatments; 2022–2023 data)	Electrical conductivity of irrigation water (ECiw) values greater than 3.4 dS m^{-1} increase soil salinity, pH, and the sodium-adsorption ratio (SAR); when ECiw exceeds 7.1 dS m^{-1}, soil aggregate stability deteriorates significantly and crop yields decline significantly,	Yuan et al., 2024

No.	Type of water	System of crops	Technique	Location	Duration	Results	References
						demonstrating a threshold-type response that leads to progressive long-term soil degradation.	
5	EC treatments ≈ 2.5, 6.0, 9.0 $dS{\cdot}m^{-1}$ (nutrient solutions)	Tomato (hydroponic)	Greenhouse hydroponic trial	(Greenhouse)	Single season	Genotypic variation and the applied nutrient regime modulate salinity responses, whereby elevated electrical conductivity suppresses vegetative growth yet exerts heterogeneous effects on fruit quality, and practices such as grafting and optimized fertilisation can partially offset these adverse impacts.	Madugundu et al., 2023
6	Salinity treatments (various EC)	Pepper landraces	Greenhouse	Greece	Single season	Landrace variability in salt tolerance permits certain genotypes to sustain fruit quality under saline irrigation, underscoring the need of genotype selection when reusing reverse-osmosis concentrate for agricultural production.	Ntanasi et al., 2024
7	Saline irrigation scenarios (varied EC)	Bitter gourd	Modelling + field data	Pakistan	2019	AquaCrop simulations reveal that water productivity and crop production fall progressively with growing irrigation salinity, although the model provides a helpful decision-support tool for maximizing reverse-osmosis concentrate reuse in agricultural planning.	Soomro et al., 2020

No.	Type of water	System of crops	Technique	Location	Duration	Results	References
8	Saline irrigation (various EC)	Multiple crops	Meta-analysis	Global (meta-analysis)	-	Saline irrigation lowers average agricultural production by ≈17.3 % and water productivity relative to freshwater, with loss magnitude varies among crops and management approaches, underlining the necessity for crop-specific studies before implementing reverse-osmosis concentrate for irrigation	Cheng et al., 2021
9	Brackish solutions (~2500 ppm ≈ 2.5 $g \cdot L^{-1}$	Two crops (hydroponic trial)	Lab & greenhouse FO + hydroponic trials	(lab/greenhouse)	Single season	Forward osmosis-produced nutrient-concentrated streams can be re-balanced to acceptable ion ratios and used as saline hydroponic solutions, enabling a sustainable feed supply that sustains plant growth and production following adequate nutrient adjustment.	Bassiouny et al., 2023
10	Rotational saline/fresh irrigation (various salinities)	Tomato (greenhouse)	Greenhouse field trial	China (Xinjiang)	2 seasons	Growers were able to control the negative effects of salinity by rotating irrigation between fresh and saline water, which changed the root environment and guaranteed fresh water availability during crucial growth stages.	Xin et al., 2025

CONCLUSION

This review highlights that reverse osmosis concentrate, traditionally regarded as a problematic waste stream, represents a dual challenge and opportunity within sustainable water and agricultural management. The evidence consistently demonstrates that, when unmanaged, RO concentrate poses significant risks to soil health, aquatic ecosystems, and long-term productivity; however, when scientifically controlled, it can serve as a supplementary source of water and nutrients, particularly in water-limited and arid regions. Overall, the existing literature provides moderate to strong evidence supporting cautious reuse strategies, especially in hydroponic systems, halophyte cultivation, and blended irrigation approaches, although findings remain highly site- and crop-specific. From a practical perspective, researchers and practitioners are encouraged to prioritise precise dilution protocols, continuous monitoring of soil salinity and sodicity, and the application of appropriate soil amendments to safeguard agronomic and environmental integrity. At the same time, the review underscores the necessity for interdisciplinary collaboration among engineers, agronomists, environmental scientists, and policymakers to translate experimental success into scalable and regulated practice. Further long-term, field-based studies are essential to clarify cumulative soil effects, crop responses, and public health implications, thereby strengthening the evidence base needed to safely integrate RO concentrate reuse into circular water systems and resilient agricultural frameworks.

AUTHOR CONTRIBUTIONS

Author	**Contribution**
Muhammad Aqeel*	Substantial Contribution to study design, analysis, acquisition of Data Manuscript Writing Has given Final Approval of the version to be published
Hamza Rehman	Substantial Contribution to study design, acquisition and interpretation of Data Critical Review and Manuscript Writing Has given Final Approval of the version to be published
Abdul Rehman	Substantial Contribution to acquisition and interpretation of Data Has given Final Approval of the version to be published
Nimra Mubarak	Contributed to Data Collection and Analysis Has given Final Approval of the version to be published

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