Published by

British Journal of Contemporary Research

BEXFORD PUBLISHING

Zero Liquid Discharge in Indian Industry: Legal Architecture, Environmental Trade-offs, and a Risk-Based Pathway toward Minimal Liquid Discharge: A Critical Review

Review Article | Volume 1 | Issue 4 | 2026 | Article Number: 047

Accepted: 02 September 2026 | Published: 10 September 2026 | ISSN: 2979-8582 (Online)

Crossref **: https://doi.org/10.67693/BJCR-89K3CKML**

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Abstract

Zero Liquid Discharge (ZLD) is increasingly used to control industrial wastewater where water scarcity, receiving-water vulnerability, high salinity, or judicial and regulatory pressure make conventional discharge unacceptable. In India, however, ZLD is often discussed as though it were a uniform statutory obligation across industries. This critical review re-examines that assumption by integrating peer-reviewed evidence on ZLD and brine management with India's statutory framework, sector-specific standards, judicial principles, and selected industrial-cluster experience. The analysis shows that the Water (Prevention and Control of Pollution) Act, 1974, and the Environment (Protection) Act, 1986, primarily establish consent, standards, and enforcement architectures; ZLD emerges through sectoral notifications, consent conditions, administrative directions, and judicial intervention rather than from a single nationwide ZLD statute. Technologically, high water recovery can reduce freshwater abstraction and liquid discharge, but the final concentration step shifts burdens toward energy use, greenhouse gas emissions, scaling and fouling control, and salt or hazardous residue management. Evidence from Tiruppur illustrates both the pollution-control gains and institutional costs of rapid ZLD adoption, whereas the Jajmau tannery cluster demonstrates the continuing importance of common effluent treatment and targeted ZLD components rather than a one-size-fits-all model. The review therefore proposes a tiered decision framework in which mandatory ZLD is reserved for high-risk settings and, elsewhere, is complemented by minimal liquid discharge (MLD), fit-for-purpose reuse, resource recovery, common infrastructure, and enforceable discharge limits. The central policy implication is that wastewater regulation should target environmental outcomes across the water-energy-carbon-waste nexus, not merely the absence of a liquid outlet.

Keywords: Zero Liquid Discharge, Minimal Liquid Discharge, Industrial Wastewater, Environmental Regulation, India, Brine Management, Circular Economy, Water-Energy Nexus

1. INTRODUCTION

Industrial wastewater regulation in India sits at the intersection of three persistent pressures: deterioration of receiving-water quality, growing competition for freshwater, and the economic dependence of industrial clusters on water-intensive production. These pressures are particularly visible in textile dyeing and finishing, leather processing, pulp and paper production, chemicals, power generation, and other sectors that generate saline, refractory, or toxic waste streams. Conventional end-of-pipe treatment can reduce organic and suspended loads, but it does not necessarily address elevated total dissolved solids (TDS), problematic ions, or the cumulative effects of industrial withdrawals in water-stressed basins.

ZLD responds to this problem by treating wastewater to recover reusable water and concentrating the remaining contaminants into a small-volume brine or solid residue. The modern ZLD concept, therefore, combines water recovery with concentrate management rather than relying on a single treatment unit. Typical systems integrate source segregation and pretreatment with biological or physicochemical treatment, reverse osmosis (RO), and, when required, high-recovery membrane concentration, evaporation, and crystallization (Tong & Elimelech, 2016; Cipolletta et al., 2021; Date et al., 2022; Yaqub & Lee, 2019). This architecture can sharply reduce liquid discharge and freshwater demand, but the final increments of water recovery are usually the most energy- and cost-intensive.

The policy appeal of ZLD is intuitive: if no liquid effluent leaves a facility, direct aqueous pollution should decline. Yet the environmental accounting is more complex. Concentrating dissolved salts and metals creates solid or semi-solid residues requiring secure storage, recovery, or disposal; thermal concentration can increase electricity or steam demand; membrane scaling and chemical conditioning create additional material burdens; and poorly managed recovered salts can re-enter the environment. For these reasons, ZLD may transform a water-pollution problem into an energy, carbon, and solid-waste problem unless the entire treatment chain is governed as one system (Tong & Elimelech, 2016; Panagopoulos et al., 2019; Panagopoulos & Haralambous, 2020).

A second problem is legal characterization. Public and policy discourse sometimes describes ZLD as a generally applicable requirement for Indian industry. That description is too broad. The core national statutes establish pollution-control boards, consent mechanisms, discharge standards, regulatory powers, and liability principles. ZLD requirements have instead developed through a more fragmented combination of sector-specific rules, consent conditions, pollution-control-board directions, location-sensitive requirements, and judicial intervention. The 2016 textile effluent amendment, for example, expressly links ZLD to large-scale units in environmentally sensitive or critical areas rather than imposing an identical ZLD obligation on every textile unit (MoEFCC, 2016a; Grönwall & Jonsson, 2017a).

This distinction matters because technology mandates can produce very different results across large integrated plants, small and medium enterprises (SMEs), and common effluent treatment plant (CETP) clusters. A technically feasible high-recovery system for a large plant may be financially unsustainable for a dispersed SME cluster. Conversely, a simple discharge-standard approach may be environmentally insufficient where receiving waters have little assimilative capacity or where high salinity threatens groundwater and agriculture.

Accordingly, this review has four objectives: (i) to clarify what ZLD technically achieves and what burdens it transfers; (ii) to locate ZLD within India's actual statutory, regulatory, and judicial architecture; (iii) to compare sector- and cluster-specific implementation constraints using textile and tannery experience; and (iv) to propose a risk-based framework for choosing among ZLD, minimal liquid discharge (MLD), common treatment, reuse, and regulated discharge. The novelty of the review lies in linking technological feasibility to legal design through the water-energy-carbon-waste nexus, rather than treating ZLD either as a purely engineering solution or as a purely legal command.

2. REVIEW APPROACH AND ANALYTICAL FRAMEWORK

This study employs a critical narrative review design, integrating engineering literature with primary and secondary legal materials. The aim is explanation and evaluation, not meta-analysis of treatment performance. The peer-reviewed sources were carefully selected to represent fundamental ZLD concepts, modern membrane-based MLD/ZLD techniques, brine and residue management, and documented Indian cluster experience. Sources were ranked on the basis of transparency of process descriptions, field scale evidence or direct relevance to India. Legal obligations have been identified on the basis of primary legal materials as authoritative sources.

These materials include the Water (Prevention and Control of Pollution) Act, 1974; the Environment (Protection) Act, 1986 and relevant Environment (Protection) Rules; the National Green Tribunal Act, 2010; sectoral notifications such as the Environment (Protection) Fifth Amendment Rules, 2016 for textile effluent; and the Water (Prevention and Control of Pollution) Amendment Act, 2024. Judicial principles were cross-checked against reported Supreme Court decisions, especially Indian Council for Enviro-Legal Action v. Union of India and Vellore Citizens' Welfare Forum v. Union of India. Administrative evidence was used where it documented implementation, for example National Mission for Clean Ganga (NMCG) and Press Information Bureau material on the Jajmau tannery CETP. The synthesis was organized around four analytical questions: (1) What environmental problem is the regulation intended to control? (2) Which ZLD or MLD process step addresses that problem? (3) What environmental burden is shifted to energy use, chemicals, air emissions, or residual solids? and (4) Which institutional actor bears the capital, operating, monitoring, and disposal responsibility? This framework allows legal stringency to be assessed together with technological and organizational feasibility. Because the study is a targeted critical review rather than a protocol-driven systematic review, it does not claim exhaustive coverage of every state pollution-control-board consent condition, court order, or industrial ZLD installation in India. State-level requirements can also change over time. The paper therefore distinguishes national statutory principles from sectoral or location-specific implementation and uses case studies illustratively rather than as nationally representative samples.

3. RESULTS OF THE CRITICAL SYNTHESIS

3.1 ZLD as a process train, not a single technology

A ZLD system is better understood as a sequence of separation and concentration steps. Upstream pretreatment removes suspended solids, biodegradable organics, hardness-forming species, oils, or specific toxicants that would otherwise impair high-recovery units. Membrane stages then recover a large fraction of water while producing progressively more concentrated reject streams. When brine salinity approaches the pressure or scaling limits of conventional RO, treatment may shift to alternative high-recovery membrane configurations, mechanical vapor compression, multi-effect evaporation, or crystallization. The final product is a mixture of reusable water, salts, sludge, crystals, or mixed residues that must be recovered or safely managed (Tong & Elimelech, 2016; Cipolletta et al., 2021; Date et al., 2022; Yaqub & Lee, 2019). The crucial environmental insight is that the last fraction of water is disproportionately difficult to recover. Conventional RO is constrained by osmotic pressure and practical module-pressure limits at high salinity. Process modeling for low-salt-rejection RO has shown that staged membrane systems can extend concentration while using less energy than traditional phase-change concentration in appropriate applications, illustrating why MLD can sometimes capture much of ZLD's water-saving benefit without forcing every stream through thermal crystallization (Wang et al., 2020). This does not imply that thermal systems are obsolete. Evaporators and crystallizers remain important in applications requiring extremely high recovery, salt crystallization, or hazardous brine containment. Their disadvantage is the energy intensity of vaporization and the associated dependence on heat integration, electricity mix, steam source, and scale control. Thus, 'zero discharge' at the fence line cannot by itself establish environmental superiority; the relevant comparison is between treatment trains on a life-cycle basis.

3.2 Environmental trade-offs across the water-energy-carbon-waste nexus

Water benefit: ZLD can materially reduce freshwater abstraction when the recovered permeate or condensate is of sufficient quality for reuse in washing, cooling, boiler feed preparation, or process applications. In water-scarce industrial clusters, avoided freshwater demand can be as important as avoided pollutant discharge. Field-scale textile experience in India has shown that water and salt recovery can be technically achievable, although performance depends strongly on influent segregation and plant operation (Vishnu et al., 2008; Jahan et al., 2022). Energy and carbon burden. Brine concentration becomes progressively more energy-intensive as salinity rises. Thermal concentration is particularly sensitive to heat-recovery configuration and energy source. Even when direct liquid discharge is eliminated, additional electricity or steam demand can increase indirect greenhouse-gas emissions unless supplied by low-carbon energy or offset by substantial resource-recovery gains (Tong & Elimelech, 2016; Panagopoulos & Haralambous, 2020; O'Connell et al., 2024; Abdelfattah & El-Shamy, 2024). Solid and hazardous residues. ZLD converts dissolved constituents into smaller-volume, higher-concentration streams. Mixed salts contaminated with dyes, organics, chromium, or other metals may have little market value and can require controlled disposal. The legal and environmental success of ZLD therefore depends on traceability and final management of residual salts and sludge. Where residues meet hazardous-waste criteria, the Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016 become directly relevant to storage, transport, treatment, and disposal (MoEFCC, 2016b). Chemical use and operational robustness. Antiscalants, pH adjustment, softening chemicals, coagulants, cleaning agents, and membrane-replacement cycles can materially affect cost and waste generation. High nominal recovery is not equivalent to reliable compliance if the system is frequently bypassed, under-loaded, or shut down due to scaling. Regulatory design must therefore account for uptime, online monitoring, concentrate mass balance, and residue destinations, not only installed design capacity.

Table 1. Sector-specific wastewater characteristics and implications for ZLD/MLD

Sector	Dominant wastewater challenge	Main ZLD/MLD bottleneck	Preferred regulatory/technical emphasis
Textile dyeing and finishing	High TDS and color; variable pH; dyes, auxiliaries, surfactants and refractory organics	RO fouling/scaling; salt quality and reuse; energy demand for reject concentration	Source segregation, salt/water reuse, CETP support for clusters, high-recovery/ZLD where location risk justifies it

Tanneries	Chromium-bearing streams, sulfides, high organic load, salinity	Need for chrome segregation/recovery; toxic sludge; mixed-stream treatment complexity	Mandatory stream segregation and chrome recovery; CETP/common infrastructure; targeted high-recovery steps with secure hazardous-residue management
Pulp and paper	High biodegradable/refractory organics, lignin-derived color, suspended solids; site-specific salinity	Organic fouling; evaporator scaling; large hydraulic loads	Process-water reduction and internal recycling first; advanced biological/oxidative treatment; MLD/ZLD only where water balance and receiving-water sensitivity support it
Chemical/pharmaceutical and mixed high-TDS streams	Highly variable salts and organics; potentially toxic or poorly biodegradable compounds	Compatibility of mixed brines, hazardous residues, and high pretreatment demand	Segregate high-strength streams; risk-based concentration; strict residue traceability and mass-balance monitoring

Note: The table deliberately avoids presenting one set of discharge limits as universally applicable across sectors. Applicable standards depend on the relevant Schedule, notification, consent conditions, receiving environment, and subsequent amendments.

Table 1 summarizes the sector-specific characteristics of industrial wastewater and highlights their key implications for the technical feasibility, treatment intensity, and selection of ZLD or MLD strategies.

3.3 Indian legal architecture: standards and consent rather than a single ZLD statute

The Water (Prevention and Control of Pollution) Act, 1974 establishes the institutional basis for water-pollution control through the Central and State Pollution Control Boards and, subject to the Act's territorial and amendment architecture, the consent regime for new outlets and discharges. The statutory logic is therefore primarily one of prevention, consent, conditions, inspection, sampling, and enforcement. It does not contain a general clause requiring every industrial establishment to achieve ZLD (Government of India, 1974). The Environment (Protection) Act, 1986 provides broader central powers to protect and improve environmental quality and prohibits industries from discharging pollutants above prescribed standards. The Environment (Protection) Rules operationalize this approach through general and industry-specific standards and allow more stringent requirements where local conditions justify them. ZLD can consequently appear as a sector- or location-specific condition within a standards-based statutory structure rather than as a universal replacement for discharge standards (Government of India, 1986; MoEFCC, 2016a). The 2016 amendment for textile effluent is especially important because it illustrates this conditional design. The notification revised effluent standards for specified textile units and included ZLD for large-scale units in environmentally sensitive or critical areas. This formulation is inconsistent with the simplified claim that all textile units throughout India are subject to one identical statutory ZLD duty. Legal scholarship on the textile sector similarly describes the framework as a combination of national standards, state-level implementation, judicial pressure, and uneven compliance capacity (Grönwall & Jonsson, 2017a). Environmental adjudication has nevertheless strengthened the normative basis for stringent pollution control. In Indian Council for Enviro-Legal Action v. Union of India, the Supreme Court linked the polluter-pays principle to remediation costs. In Vellore Citizens' Welfare Forum v. Union of India, the Court treated the precautionary principle and polluter-pays principle as part of Indian environmental law. Section 20 of the National Green Tribunal Act, 2010 subsequently requires the Tribunal to apply sustainable development, the precautionary principle, and the polluter-pays principle when deciding matters within its jurisdiction (Government of India, 2010; Indian Council for Enviro-Legal Action v. Union of India, 1996; Vellore Citizens' Welfare Forum v. Union of India, 1996). These principles support stringent controls where the environmental risk warrants them, but they do not logically require one technology in every context. Precaution asks regulators to prevent serious or uncertain harm; polluter pays allocates the cost of pollution and remediation; sustainable development requires integration of environmental and economic considerations. A performance-based rule can therefore be as legally defensible as a technology mandate if it achieves equivalent or better environmental outcomes and is enforceable. The Water (Prevention and Control of Pollution) Amendment Act, 2024 further altered parts of the consent and penalty architecture. Because the Water Act is rooted in Article 252 of the Constitution and amendments may have state-specific application and adoption histories, researchers and regulated entities should verify the version in force in the relevant state at the time of compliance. This federal feature is another reason to avoid describing ZLD as a single, nationally uniform legal command (Government of India, 2024).

Table 2. Principal legal instruments and their relevance to industrial ZLD

Instrument	Core legal function	Relevance to ZLD analysis
Water (Prevention and Control of Pollution) Act, 1974	Pollution-control boards, consent, monitoring, directions, and control of sewage/trade effluent discharge	Provides the core water-pollution governance architecture; does not itself create a universal ZLD mandate
Environment (Protection) Act, 1986 and Rules	Central power to prescribe standards and issue directions; industry-specific and general discharge standards	Legal route through which sector-specific requirements and more stringent local conditions may be imposed
Environment (Protection) Fifth Amendment Rules, 2016 - textile effluent (G.S.R. 978(E))	Revised textile effluent standards and location-sensitive ZLD provision	Demonstrates conditional ZLD for large-scale units in environmentally sensitive/critical areas rather than blanket coverage
Hazardous and Other Wastes (Management and Transboundary Movement) Rules, 2016	Management, authorization, storage, movement and disposal of hazardous/other wastes	Relevant when ZLD sludge, salts or concentrates meet applicable hazardous-waste classifications
National Green Tribunal Act, 2010, s. 20	Requires application of sustainable development, precautionary and polluter-pays principles	Strengthens outcome-based environmental responsibility and remediation logic

Water (Prevention and Control of Pollution) Amendment Act, 2024	Changes elements of consent/penalty architecture with state-specific application/adoption considerations	Requires current-state verification; reinforces that compliance analysis must identify the applicable statutory version and local consent conditions

Table 2 summarizes the principal legal and regulatory instruments governing industrial wastewater management in India and highlights their relevance to the implementation and enforcement of ZLD requirements.

3.4 Enforcement is the binding constraint

The environmental performance of ZLD depends less on the label attached to the plant than on continuous operation, verifiable mass balance, and credible enforcement. A facility can formally possess a high-recovery system yet remain non-compliant if untreated streams are bypassed, if reject is discharged intermittently, or if contaminated salt is dumped outside the regulated waste-management chain. Conversely, a well-operated MLD or CETP system with robust monitoring can outperform a nominal ZLD system that is economically unstable. This creates a regulatory paradox. More stringent technology requirements can raise compliance costs so sharply that incentives for evasion increase, especially in fragmented SME clusters. The appropriate policy response is not necessarily to weaken standards; rather, it is to match obligations with common infrastructure, financing, metering, online monitoring, transparent residue tracking, and penalties that are both credible and proportionate. The polluter-pays principle is most effective when the cost of non-compliance is predictable and enforceable, while the cost of compliance is technically feasible.

3.5 Case evidence from Indian industrial clusters

3.5.1 Tiruppur textile cluster: rapid ZLD uptake with institutional trade-offs

Tiruppur, Tamil Nadu, is the most frequently cited Indian example of cluster-scale ZLD in textile wet processing. Its evolution was driven by severe pollution of the Noyyal River system, litigation, regulatory action, and the economic importance of the export-oriented textile cluster. Field-scale studies reported technical recovery of water and salts from textile effluent, while later socio-technical analysis documented the governance, financing, energy, and compliance challenges involved in moving toward ZLD (Vishnu et al., 2008; Grönwall & Jonsson, 2017b). The Tiruppur experience supports two conclusions. First, strong regulatory and judicial pressure can accelerate investment in common treatment and high-recovery technologies when a receiving environment has already exceeded acceptable pollution burdens. Second, infrastructure installation is not the end of the regulatory problem. Energy demand, operating cost, sludge and salt management, membrane/evaporator performance, collective-action problems, and the distribution of costs among firms remain central to long-term compliance. The case therefore favors a systems interpretation of ZLD rather than a binary 'discharge/no-discharge' metric.

3.5.2 Jajmau tannery cluster: common treatment plus targeted ZLD components

The Jajmau tannery cluster in Kanpur provides a useful contrast because tannery wastewater combines organic load, salinity, sulfide, and chromium-bearing streams (Ricky et al., 2022). In 2018, the National Mission for Clean Ganga approved a project centered on a 20 MLD CETP with pretreatment at individual tanneries and a 200 KLD ZLD-based pilot component, rather than describing the entire 20 MLD treatment flow as a stand-alone full-scale ZLD system (Press

Information Bureau, 2018). This configuration recognizes the need for common infrastructure and stream-specific controls in a dense SME cluster. By the end of 2025, the Government reported that construction of the 20 MLD Jajmau CETP had been completed and the facility was in testing, commissioning, and performance-guarantee testing (Press Information Bureau, 2025). The implementation trajectory illustrates the institutional time, capital, and coordination required for cluster-scale industrial pollution control. It also shows why legal analysis should distinguish between a ZLD pilot or concentrate-management component and the treatment architecture of the entire cluster. For tannery regulation, chromium segregation and recovery, sulfide management, source pretreatment, CETP performance, secure sludge handling, and enforceable monitoring may be more environmentally important than requiring every small tannery to operate its own thermal crystallizer. A risk-based framework can still require higher recovery where local water scarcity, groundwater vulnerability, or receiving-water conditions make residual discharge unacceptable.

4. DISCUSSION: FROM UNIVERSAL ZLD RHETORIC TO RISK-BASED WASTEWATER GOVERNANCE

4.1 Why MLD can be an environmentally rational intermediate endpoint

MLD seeks very high water recovery while allowing a controlled residual stream to remain for further treatment or regulated disposal. Its value is not that some discharge is inherently desirable, but that the marginal environmental cost of recovering the final fraction of water can exceed the benefit in some settings. Where thermal crystallization would require substantial fossil-derived energy and produce mixed salts with no viable recovery pathway, an MLD configuration with stringent discharge limits may have a lower total environmental burden (Wang et al., 2020). The appropriate comparison is therefore outcome-based: freshwater withdrawal avoided; pollutant and salt mass prevented from entering receiving waters; energy consumed; greenhouse gas emissions; chemical demand; hazardous residue quantity and destination; operational reliability; and compliance probability (Panagopoulos, 2022; O'Connell et al., 2024). ZLD should be preferred when its total outcome is superior, especially in high-risk settings. It should not be treated as environmentally self-proving merely because the liquid outlet is eliminated.

4.2 A tiered decision framework for Indian regulators and industries

A defensible regulatory framework can combine mandatory performance outcomes with technology-specific requirements triggered by risk. The first decision variable is receiving-environment vulnerability: water-stressed basins, critically polluted areas, groundwater-dependent regions, and sensitive ecosystems justify higher recovery. The second is pollutant character: persistent toxicants, problematic salinity, and metal-bearing streams justify stricter segregation and containment than readily biodegradable low-salinity effluent. The third is industrial organization: a large integrated plant can internalize advanced treatment more easily than hundreds of SMEs, for which common treatment and shared concentrate management may be more enforceable. The fourth variable is life-cycle feasibility. Regulators should require a water and salt mass balance, specific energy consumption, residue characterization, disposal/recovery route, and contingency plan before approving ZLD as the compliance pathway. This shifts regulatory attention from installed equipment to verified environmental performance.

Table 3. Proposed risk-based hierarchy for selecting ZLD, MLD, or regulated discharge

Risk/setting	Preferred compliance pathway	Key safeguards
High risk: critically polluted or environmentally sensitive area;	High-recovery treatment with ZLD, where	Online flow/quality monitoring; full water/salt mass balance;

severe water stress; high salinity/toxicity; large or technically capable unit	life-cycle assessment and residue route are credible	secure residue disposal or verified recovery; energy reporting; bypass prevention
Moderate risk: reusable water has value, but the receiving environment retains controlled assimilative capacity	MLD plus fit-for-purpose reuse and stringent residual-discharge limits	Defined minimum recovery; concentrate treatment; receiving-water monitoring; periodic energy and residue audit
SME industrial cluster with compatible effluent streams	CETP/common RO or high-recovery facility, with source-specific pretreatment	Individual flow metering; pollutant-load allocation; source segregation; collective O&M financing; common sludge/concentrate tracking
Lower salinity and readily treatable effluent outside sensitive areas	Best-available treatment plus enforceable discharge standards and reuse incentives	Consent limits; toxicity/priority-pollutant control; water-efficiency benchmarks; escalation trigger if receiving-water quality deteriorates

Table 3 presents a proposed risk-based decision hierarchy for selecting among ZLD, MLD, and regulated discharge based on wastewater characteristics, environmental sensitivity, water scarcity, regulatory requirements, and treatment feasibility.

4.3 Policy priorities: Make ZLD triggers explicit.

Sectoral rules and consent orders should state why ZLD is required, using measurable triggers such as basin water stress, receiving-water sensitivity, pollutant salinity/toxicity, plant scale, and availability of safe concentrate disposal. This improves predictability and reduces the risk of technology mandates being applied inconsistently. Regulate the concentrate and solids, not only the permeate. Every ZLD/MLD consent should include a concentrate mass balance, residue classification, storage limits, transport documentation, authorized recovery/disposal destination, and reconciliation between influent salts and recovered/disposed mass. Use shared infrastructure for SME clusters. CETPs, common RO/high-recovery systems, common chrome recovery, and shared evaporators can reduce duplication and improve professional operation where individual units lack technical capacity. Cost allocation should be linked to measured flow and pollutant load to reduce cross-subsidy and dilution incentives. Link water recovery to energy and carbon reporting. High recovery should be accompanied by reporting of specific energy use and, where material, carbon intensity. Energy-efficient membrane concentration, heat integration, waste-heat use, and renewable electricity should be encouraged when technically compatible. Prioritize source reduction before end-of-pipe concentration. Cleaner production, counter-current rinsing, bath reuse, dry processing, segregated high-strength streams, chemical substitution, and water pinch approaches can reduce hydraulic and salt loads before they reach expensive recovery units. Adopt enforceable escalation pathways. A facility or cluster operating under MLD or regulated discharge should face predefined escalation toward higher recovery if receiving-water quality deteriorates, consent violations persist, or local water stress crosses a regulatory threshold. Support transparent compliance data. Publicly accessible monitoring for major clusters should include influent and effluent flow, key pollutants, plant downtime, concentrate generation, and final residue destination. Transparency can improve both enforcement credibility and community trust. 4.4 Circular-economy opportunities and their limits Resource recovery can improve ZLD economics when recovered materials have stable quality and a credible market. Examples include reuse-quality water, sodium salts from suitably segregated textile streams, chromium recovery from segregated tannery liquors, and recovery of selected nutrients or chemicals from sufficiently clean process streams. The strongest circular-economy cases occur when source segregation prevents valuable streams from being contaminated before recovery (Yaqub & Lee, 2019; Cipolletta et al., 2021; Panagopoulos, 2022). However, circularity claims require quality control. A crystallizer that produces mixed contaminated salt does not automatically create a resource; it may simply create a concentrated waste. Policy should therefore distinguish 'recovered product' from 'residue' using product-quality specifications, contaminant thresholds, traceability, and demonstrated end use. This prevents nominal recycling from becoming uncontrolled secondary disposal.

5. LIMITATIONS AND RESEARCH AGENDA

The available Indian evidence remains uneven, while recent reviews similarly identify persistent gaps in life-cycle, concentrate-management, and techno-economic evidence (Date et al., 2022; Abdelfattah & El-Shamy, 2024). Published field data frequently report treatment performance or water recovery without a full life-cycle inventory of electricity, steam, chemicals, membrane replacement, salt purity, sludge classification, and final disposal. Comparative studies that place ZLD, MLD, and optimized conventional treatment on a common functional basis are still limited. Future work should report at least water recovery, pollutant mass removal, specific energy consumption, operating cost, greenhouse-gas intensity, concentrate quantity/composition, residue fate, and plant availability.

Legal research also needs finer state-level resolution. Consent conditions and pollution-control-board directions can be more stringent than national minimum standards, while Article 252 creates state-specific dimensions in the Water Act and its amendments. A periodically updated database of state-level ZLD/MLD conditions, affected sectors, thresholds, and judicial orders would materially improve both scholarship and compliance planning.

A third research need is institutional performance. Engineering studies rarely quantify the effect of tariff design, common-plant governance, downtime incentives, enforcement frequency, or data transparency on actual compliance. Cluster-scale wastewater management should be studied as a coupled technical-institutional system. Longitudinal evidence from Tiruppur, Jajmau, and other industrial clusters can reveal whether high-recovery systems remain environmentally and financially sustainable beyond the commissioning phase.

Finally, climate and energy policy should be integrated with water regulation. As India decarbonizes electricity and industrial heat, the environmental penalty associated with energy-intensive water recovery may decline, changing the optimal boundary between MLD and ZLD. Conversely, greater climate-driven water stress may raise the value of reuse. Regulatory frameworks should therefore be capable of adapting over time rather than locking all sectors into a static treatment prescription.

6. CONCLUSION

ZLD is a powerful wastewater-management strategy, but it is neither a single technology nor a universally superior environmental endpoint. In India, its legal basis is distributed across consent mechanisms, environmental standards, sector-specific notifications, administrative directions, and judicial principles. The central statutes establish a strong framework for pollution prevention and control, but they should not be simplified into the claim that all industries are subject to one nationwide ZLD mandate.

Technically, ZLD can reduce freshwater demand and direct liquid pollution, especially where high salinity, severe water stress, or ecological vulnerability makes conventional discharge unacceptable. Its benefits must nevertheless be weighed against energy use, carbon emissions, chemical demand, scaling/fouling risks, and the management of concentrated salts and sludge. The environmental objective is not merely to move contaminants out of water, but to prevent their transfer into another poorly governed medium. A risk-based hierarchy provides a more defensible path. Mandatory high-recovery ZLD should be reserved for settings where environmental risk and life-cycle performance justify the added burden. MLD, common treatment, source segregation, fit-for-purpose reuse, resource recovery, and stringent discharge standards can serve as complementary pathways elsewhere. The regulatory focus should shift from the symbolic presence of 'zero liquid discharge' equipment to verified outcomes across the water-energy-carbon-waste nexus. Such an approach better aligns Indian industrial water governance with the precautionary principle, polluter pays, sustainable development, and the practical realities of heterogeneous industrial clusters.

Author contributions

Ghilman Sarmad: Conceptualization, legal analysis, writing - original draft. *Md Aqdas:* Literature synthesis, writing, review, and editing. *Aleena Shahzad:* Environmental analysis, visualization, writing, review, and editing. *Asad Anwar:* Sectoral analysis, visualization, writing, review, and editing. *Md Sharif Ansari:* Technical review, writing, review, and editing. *Md Adim:* Conceptualization, supervision, technical validation, writing - review and editing. All authors have read and approved the final manuscript and accept responsibility for the work.

Funding

The authors received no specific funding for this work.

Data availability statement

No new datasets were generated or analyzed. The study is based on publicly available legal instruments, administrative documents, judicial decisions, and published literature cited in the manuscript.

Ethics approval and informed consent

Not applicable. The study did not involve human participants, animals, or identifiable personal data.

Conflict of interest

The authors declare no known financial or personal conflicts of interest that could have influenced this work.

Declaration of generative AI and AI-assisted technologies

During preparation of this manuscript, the authors used ChatGPT (OpenAI) and Grammarly for language refinement, structural organization, and drafting support. The authors subsequently reviewed and revised the AI-assisted content and took full responsibility for the accuracy, originality, interpretation, and integrity of the final manuscript.

Acknowledgments

The authors acknowledge Zakir Husain College of Engineering and Technology and the Faculty of Law, Aligarh Muslim University, Aligarh, India, for administrative and academic support.

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