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Advance membrane technology for zero liquid discharge (ZLD) effluent treatment and water recovery'

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Abstract

Zero Liquid Discharge (ZLD) systems are necessary for sustainable water management due to water scarcity and environmental regulations. Recent improvements in membrane-based technologies including RO, FO, and MD enhance water recovery and reduce liquid waste. Thin-film nanocomposites and graphene oxide-based membranes improve selectivity, permeability, fouling resistance, and energy efficiency. System hybrids with various membrane processes save money and improve performance. Energy consumption, membrane fouling, and solid waste processing restrict widespread adoption despite technological breakthroughs. Minimum Liquid Discharge (MLD) systems are also popular for resource-constrained areas due to their affordability. ZLD and MLD technologies promote water reuse, resource recovery, and industrial environmental footprint reduction, achieving global sustainability goals.

Keywords: Membrane Technology; Advancement in membrane technology; Industrial water effluent; Zero Liquid Discharge (ZLD); Water Recovery; Benefits of advanced membrane technology

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Abbreviations: *ZLD Zero Liquid discharge, MLD Minimal liquid discharge, US United States, G.M. General Motors, MD Membrane Distillation FO Forward Osmosis, RO Reverse Osmosis, OARO Osmotically Aided Reverse Osmosis*

1. Introduction

Industry, notably manufacturing and energy generation, has reduced environmental effect by implementing these measures [1]. Municipal water treatment facilities benefit from industrial ZLD systems' wastewater reduction. ZLD technologies were first utilized in US power plants in the 1970s to address rising Colorado River salinity. Many US ZLD systems remain. Recent ZLD and MLD technologies promise to reduce saline wastewater disposal's environmental impact and boost resource recovery and value [2].

ZLD/MLD systems recover metals, energy, salts, minerals, and high-purity water using many technologies [1]. Hybrid methods reduce operational costs and carbon emissions by recovering different resources and optimising energy use. Desalination with salinity gradient power technology enhances energy recovery and saves costs [3]. Desalination and wastewater treatment provide high-purity water for home, industrial, and commercial use in ZLD systems. Solid salt byproducts can be sold, recycled for industrial use, or managed sustainably. By selecting and integrating applicable technologies, ZLD operations can produce many high-purity solid products instead of one mixed solid waste stream, boosting their economic viability and environmental sustainability [4]. ZLD may work for some businesses, but low-income sectors need cheaper options. Minimal Liquid Discharge (MLD) can save manufacturers money if environmental and regulatory standards are satisfied [5]. While MLD and ZLD use similar technologies, MLD recovers up to 95% of freshwater using hybridized membranes. The MLD technique was successfully used at the GM automobile assembly site in San Luis Potosí, Mexico. This 160,000-car manufacturer recycles up to 90% of its wastewater 250 miles northwest of Mexico City [6].

Membranes were used to discharge less than 10% of effluent into evaporation ponds. Water treatment and desalination improvements have led to innovative membrane technologies for environmental and socioeconomic challenges. See OARO, FO, and MD [7]. Solute concentration and FO energy conservation are achieved by osmotic pressure pushing water over a semi-permeable barrier. MD uses hydrophobic membrane temperature difference to evaporate and condense water, saving energy. OARO works well with high-salinity brines because it recovers water and saves energy using RO and FO. Sustainable water management using membrane-based ZLD and MLD technologies is discussed in this paper. Brine management, energy efficiency, and resource recovery are priorities [8]. RO, FO, and MD membrane technologies in development and commercial use are assessed. ZLD and MLD frameworks are optimized and aligned with global sustainability programs like the UN Sustainable Development Goals using technology and case studies. Zero Liquid Discharge (ZLD) systems decrease water pollution and promote sustainability, however they may harm the ecosystem. Management of solid waste issues. Untreated solid waste in evaporation ponds stinks, harms wildlife, and pollutes ecosystems. Without sufficient containment, landfill waste can pollute groundwater. Effective monitoring and impermeable liners prevent pollution [9].

High energy demand and GHG emissions are another ZLD environmental challenge. Pretreatment techniques like acidification and degasification enhance feedwater CO_2 emissions. Electrodialysis (ED) technologies, which concentrate reverse osmosis (RO) brine, enhance CO_2 emissions through energy and decarbonization. Life-cycle research suggests that switching California's water supply from imported to inland brackish water reverse osmosis (BWRO) desalination might raise GHG emissions by 50%. The U.S. Energy Information Administration reports that MVC brine concentrators may produce 19-23 kg of CO_2 per cubic meter of treated feedwater, using 20-25 kWhe/m³ electricity and 939 g CO_2 per kWhe coal-based generation factor. RO and other energy-efficient technologies drastically reduce GHG emissions. ZLD systems reduce carbon emissions by using waste heat, solar, and geothermal energy. As water pollution awareness grows, regulatory incentives and stricter wastewater discharge limits may boost ZLD market growth despite its high price. These developments should encourage high-polluting industries to use ZLD. Water overexploitation and climate change will diminish freshwater availability, easing ZLD implementation. Extended drought in the southwestern US and increasing growth of water-intensive enterprises like coal-fired power plants in China highlight the worldwide freshwater crisis. Limiting water use may require quotas. These sectors can benefit from ZLD water recycling and recovery. Calcium carbonate, magnesium hydroxide, and gypsum-magnesium hydroxide are key byproducts of ZLD mineral precipitation and crystallization. Recovery of these materials economically benefits ZLD, minimizing waste disposal. This article critically evaluates membrane technology in industrial wastewater treatment, zero-liquid-discharge approaches, and water recovery system upgrades for environmental, technical, and economic impacts.

2. Membrane technology

Membranes transport or reject chemicals, components, and species. Many firms benefit from its interdisciplinary character. This energy-efficient, pure separation process can replace filtering, ion exchange, distillation, and chemical treatment, benefiting industry and the environment. Its versatility makes membrane technology appealing. Membranes allow some components but not others. Improved materials and methods have made membranes more versatile since the 18th century. Membranes with anisotropy. The structure and chemistry of isotropic membranes are uniform. Permeation fluxes are high for microporous membranes but low for dense isotropic membranes, limiting their use [10]. Traditional municipal water treatment employs chemical flocculation and coagulation. Because raw water quality impacts efficacy, many approaches require periodic chemical dosage changes [11]. Maintaining treated water quality without precise data and real-time monitoring is difficult. Chemical-free membrane filtering is more reliable. These chemical-free systems produce microbiologically safe drinking and sanitation water. Personalized therapy is possible using modular membrane systems. The worldwide membrane market is driven by membrane technology. From USD 5.4 billion in 2019 to USD 8.3 billion in 2024, membrane filtration will expand 9%. Water treatment needs in China, Indonesia, India, Vietnam, Thailand, and Malaysia are driving membrane technology expansion (Global Membranes Market Report, 2020). Separation uses semi-permeable membranes with thin, thick selective layers and porous substructures [12]. This selective layer blocks phases and lets just particular components through, allowing selective separation [13]. Membranes are classified by structure and composition. They are structurally homogeneous, symmetric, asymmetric, or heterogeneous. A uniform pore size and structure throughout the membrane thickness offers symmetric membranes constant transport properties. The thin, dense selective layer separates and the porous support layer provides mechanical strength and minimizes transport resistance in an asymmetric membrane. This asymmetric design reduces pressure drop and maintains separation efficiency [14]. By composition, organic (polymeric) and inorganic membranes are classed. They may be built of many materials depending on characteristics and function.

2.1. Types of Membrane technology

2.1.1. Pressure-Driven Membrane Processes

Pressure-driven membranes are essential for wastewater pre- and post-treatment. A semi-permeable membrane separates contaminants by size, molecular weight, or chemical characteristics under hydraulic pressure. Modern water and wastewater management systems require these efficient, scalable, and reliable procedures. Pressure-driven membrane processes include Microfiltration (MF), Ultrafiltration (UF), Nanofiltration (NF), and Reverse Osmosis.

Microfiltration and ultrafiltration remove suspended particles, bacteria, and macromolecules, whereas nanofiltration and reverse osmosis remove dissolved salts, organic contaminants, heavy metals, and other low-molecular-weight solutes. The most selective membrane technology, reverse osmosis, rejects monovalent ions to produce high-purity water. The hierarchical use of membrane techniques enables for customized treatment solutions to meet municipal, industrial, and environmental regulatory and reuse standards [15, 16]. After Figure1, pressure-driven membrane technology was shown.

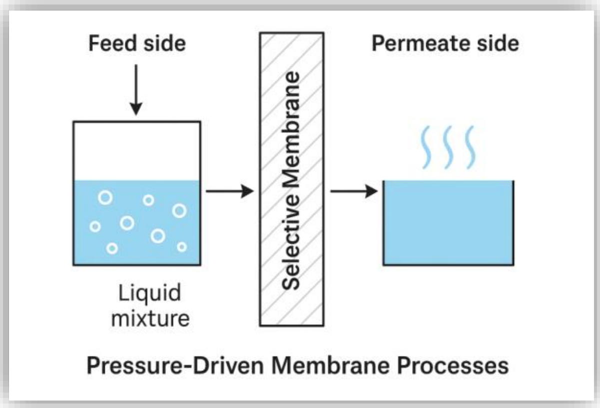

Figure1 indicated the pressure-driven membrane technology processes.

2.1.1.1. Microfiltration membrane

Membrane-based microfiltration (MF) is frequently used in wastewater treatment to remove suspended particles and macromolecular organic materials [17]. It works by sieving using a static pressure differential. MF has more precision than conventional filtration although using the same separation method. Microfiltration membranes, with pore widths of 0.1-1 µm, can remove particles with diameters of 0.13-15 µm. MF microporous membranes have different structures, resulting in three separation mechanisms: bridging, mechanical interception, and adsorptive interception, with physical interception being the most common. MF can remove suspended particles and certain bacteria, but not dissolved salts, low molecular weight chemical molecules, or heavy metal ions. The tiny size of MF membranes allows viruses to partially slip through [18,19].

Microfiltration is typically used with chemical precipitation, adsorption, and coagulation to improve heavy metal and other dissolved pollutant removal. Coprecipitation, where coagulants such ferric hydroxide transform metal ions into insoluble forms, is crucial to MF removal. This approach works well on wastewater with high heavy metal and organic matter concentrations. Large amounts of heavy metal-laden wastewater released into aquatic systems in rapidly industrializing countries like China threaten environmental and public health. By increasing heavy metal ion removal efficiency, MF with adsorption and coprecipitation procedures might mitigate this issue [20].

2.1.1.2. **Ultrafiltration membrane process**

Ultrafiltration (UF), a membrane-based separation method, has mechanically separated liquid mixture components for than a century. Ultrafiltration uses hydrostatic pressure to drive liquids through a semipermeable membrane, separating them by molecule size. This pressure-driven method eliminates suspended particles and macromolecules above the membrane's MWCO. Other parameters including molecule structure, charge, and hydrodynamic circumstances affect separation efficiency. Size exclusion is the main mechanism of UF, but solute-membrane interactions might affect separation efficiency. UF membranes have changed in material design and application. They are presently employed in chemical recovery, cell harvesting, dairy processing, medical applications, water and wastewater treatment, and juice concentration. UF is known for clarifying and disinfecting [21]. UF is often used to purify and concentrate macromolecular solutions like proteins in the food sector. UF is also important in treating industrial effluents from textile and metal processing, especially paint recovery and fouling reduction. Ultrafiltration is more sustainable and cost-effective than conventional purification and disinfection procedures due to its low energy, chemical, and operating temperatures and high-quality output.

2.1.1.3. Nanofiltration membrane processes

Nanofiltration (NF) membranes are a new wastewater treatment technology. NF membranes have pore diameters approximately 1 nm and selective permeability based on molecule size and charge. Due to their surface electrostatic characteristics, they retain multivalent ions and uncharged organic molecules while partially passing monovalent ions. NF is ideal for solute fractionation in complex process streams due to its selective separation. NF has been popular in textile pulp-bleaching effluent treatment and pharmaceutical fermentation broth recovery.

2.1.1.4. Reverse osmosis membrane processes

Reverse osmosis pushes a solvent across a semi-permeable membrane from a high-to-low solute concentration area by applying pressure greater than the osmotic pressure. Most people separate clean water from brackish and saltwater using reverse osmosis. Placing brackish or saltwater against a membrane surface transports salt-depleted water across it, creating portable drinking water [21, 22]. RO is an advanced membrane filtering method that removes viruses, larger particles, ions, chemicals, and other dissolved and suspended contaminants using a semi-permeable membrane. This method requires pressure to overcome osmotic pressure, which is 17–27 bars for brackish water and 52–69 bars for seawater. Osmotic pressure, a collision phenomenon driven by solvent chemical potential, drives this action. Diffusion dominates organic liquid separation and breaking the substantial osmotic pressure barrier [23]. RO technique was developed over a century but not introduced until early 1960. At that point, membrane technology could use desalted water. Water, the solvent, flows from the diluted solution to the concentrated solution through a semi-permeable membrane until the concentrations are equal. Osmosis describes this process.

2.1.2. Forward Osmosis membrane processes

Forward osmosis (FO) uses the natural osmotic pressure differential across a semipermeable membrane to separate fluids instead of hydraulic pressure. FO occurs when water naturally diffuses over a semipermeable membrane from the feed solution to the draw solution until osmotic equilibrium is established [18]. FO membranes are designed to selectively pass water but reject solutes. FO reduces the need for high-pressure pumps in RO systems, reducing energy usage. FO is a promising water treatment and desalination option due to its energy efficiency, less fouling, and increased solute rejection [19].

2.1.3 Electro-Dialysis (ED) and Electro-Dialysis Reversal (EDR)

The electric field drives cations toward the cathode through CEMs and anions toward the anode through AEMs. These provide alternating dilute and concentrate chambers, separating ions from feed [22]. EDR, an enhanced version of this method, reverses electrode polarity periodically. This reversal of salts reduces membrane scaling and fouling, extending membrane lifespan and enhancing operational efficiency [24]. Following **Figure2** indicated the Electrodialysis (ED) separation process.

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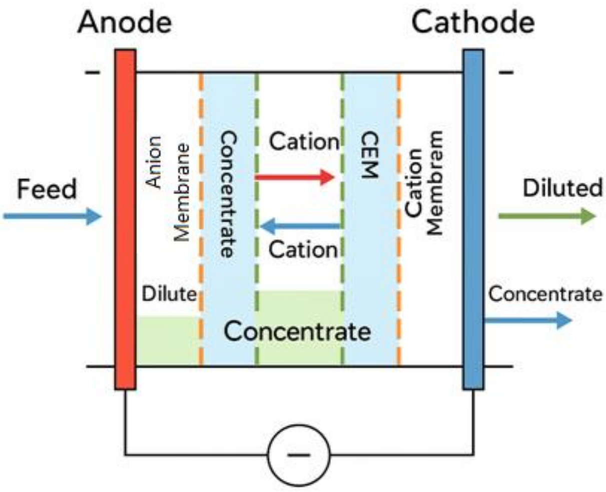

Figure2 Represent the electrodialysis (ED) separation process.

ED and EDR in wastewater treatment aim to lower TDS and other ions. High water recovery rates and minimum pre-treatment make these technologies excellent for brackish water desalination, industrial effluent treatment, and nutrient recovery. ED can precisely separate charged solutes from uncharged species in aqueous solutions because to ion exchange membranes' selective nature. Spacer gaskets define flow channels and dilute and concentrate compartments in the ED stack, whereas electrode rinse chambers circulate electrolyte solutions and maintain electrode functionality [25]. ED systems remove many impurities, including phosphorus, potassium, nitrogen, and organic and inorganic ions. Integrating renewable energy sources with ED makes water reuse and resource recovery sustainable. Electrodialysis treats ion-rich wastewater streams efficiently, scalable, and ecologically friendly using alternating ion-selective membranes and applied electrical potential [26].

2.3.4 Pervaporation processes

The membrane receives the liquid mixture while the permeate evaporates. This approach uses membrane penetration and evaporation to separate liquid mixtures by preference. On one side of the membrane, liquid mixtures are received, while permeate evaporates[27]. Permeate is absorbed upstream during this procedure. The membrane (molecularly porous inorganic or nonporous polymeric) absorbs the more permeable liquid mixture component. A diffusing species concentration differential causes these components to diffuse over the membrane and evaporate downstream. Condensation turns vapor into liquid. This membrane mass movement process is called the solution-diffusion model [28, 29]. This method is mostly used to separate ethanol from water. It is being researched for wastewater treatment in various production regions [75]. Pervaporation micro-irrigated plants with wastewater. For the experiment, a thick hydrophilic pervaporation barrier was placed in crucial soil sites. Permeate waves blasted across synthetic wastewater feed tank membranes. We monitored wastewater enrichment and flow (contaminant rejection). The findings suggest this approach can treat wastewater or brackish ground water for micro-irrigation. Pilot-scale experiments removed benzene, toluene, napthala, butane, ethyl ether, and other organic solvents from diluted water [30]. Following **Figure3** indicated the pervaporation processes through membrane

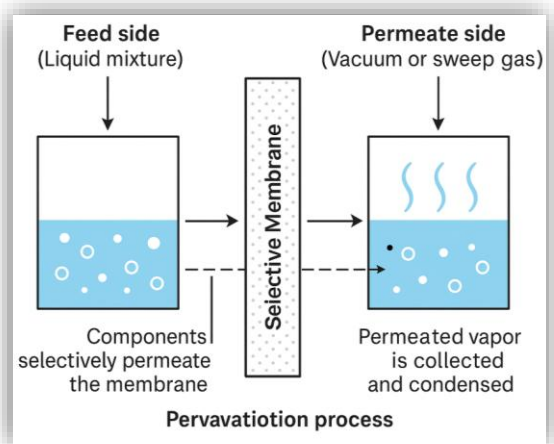

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Figure3 Represents the pervaporation processes through membrane

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Category	Technology	Key Features	Applications
A) Pressure-Driven Membrane Processes	Microfiltration (MF)	Pore size: 0.1–1 µm. Mechanism: Sieving, bridging, adsorption Removes suspended solids, some organics	Pretreatment, Removal of heavy metals, Textile and chemical industries
	Ultrafiltration (UF)	MWCO-based separation, Pore size: ~0.01–0.1 µm, Mechanism: Size exclusion.	Clarification, disinfection. Food and dairy industries. Wastewater reclamation
	Nanofiltration (NF)	Pore size: ~1 nm. Allows monovalent ions, retains multivalent ions. Mechanism: Electrostatic interactions	Textile effluent treatment. Pharmaceutical separation. Water softening
	Reverse Osmosis (RO)	Removes ions, molecules, viruses. Pressure: 17–27 bar (brackish), 52–69 bar (seawater). Mechanism: Diffusion	Desalination. Drinking water purification. Industrial water reuse
B) Osmotic Process	Forward Osmosis (FO)	No hydraulic pressure. Osmotic pressure driven. Low energy consumption	Brine concentration, Wastewater treatment, Emergency water supply
C) Electrically Driven Processes	Electrodialysis (ED) & Electrodialysis Reversal (EDR)	Removes ions using electric potential, Uses AEMs and CEMs, High water recovery	Desalination, Ion removal, Integration with renewable energy
D) Thermally Driven Process	Pervaporation	Combines membrane permeation & evaporation. Mechanism: Solution-diffusion. Permeate evaporates, then condenses	Separation of organics (e.g. ethanol, benzene). Micro-irrigation using wastewater. Removal of VOCs from water

Table1: Represents the types of membrane technologies, their features and applications.

3. Advancement in membrane technology

Population growth and industrial pollution are causing global water scarcity. In particular, industrial effluents pollute water, necessitating effective and sustainable water treatment technology. Membrane technology is popular because of its low cost and adaptability. Traditional membrane materials frequently have poor chlorine, extreme pH, high temperature, and organic solvent resistance, as well as aperture shrinking at high pressure [24]. Recent advances have shown that carbon-based nanomaterials including CNTs, graphene, and graphene oxide (GO) can overcome these problems. These materials are ideal for next-generation membrane manufacturing due to their mechanical strength, chemical stability under demanding circumstances, and solvent compatibility [25]. The two-dimensional structure and atomic-scale thickness of graphene oxide provide it great surface area, mechanical resilience, and chemical inertness. Its almost frictionless surface, flexibility, and large-scale, solution-based manufacture make it a viable nano-building block for improved separation membranes [26–28].

3.1. Energy efficient and sustainable membrane technologies

Distillation and crystallization pollute the environment. Energy-saving membrane barriers selectively allow particular molecules or ions to pass. Selectivity reduces phase transitions in thermal processes, saving energy. Reverse osmosis (RO) removes salts and other contaminants from seawater with less energy than thermal techniques [33].

3.1.1. Sustainable Membrane Technology

Water molecules move through these membranes, capturing suspended solids, dissolved particles, and other pollutants for efficient filtration [34]. Increasing dissolved salts in water sources causes public health issues because saline water is inappropriate for food and crops. Nanofiltration, microfiltration, and reverse osmosis membrane-based desalination remove salts and other dissolved contaminants from contaminated water.

Rising global freshwater demand requires advanced desalination methods. Some thermal desalination applications still employ Multi-Effect Distillation (MED), Multi-Stage Flash Distillation (MSFD), and Membrane Vacuum Distillation (MVD), but membrane technologies are replacing them because to their reduced energy and environmental impact [35]. These ideas solve water scarcity and security sustainably.

4. Benefits of advanced membrane technology

Several membrane technology techniques extract components from fluid mixes based on molecular size, charge, and chemical affinity using semipermeable membranes [36]. Adaptable, it is used in water purification, medicine, food processing, and renewable energy [41]. Without phase changes, membrane methods are more energy-efficient and environmentally benign than distillation and crystallization. Their selective permeability boosts separation efficiency, energy use, emissions, and product purity, boosting global sustainability.

Following **Figure4** indicated the benefits of advanced membrane technology for ZLS.

Figure4. Benefits of advanced membrane technology for ZLS

In petrochemicals, pharmaceuticals, and food processing, membrane technology saves energy [42]. Because it isolates chemical contaminants and produced products, it is better than expensive and energy-intensive chromatography and solvent extraction [43]. More synthetic chemicals in pharmaceuticals, personal care, and insecticides raise environmental and public health concerns. Advanced oxidation and activated carbon are costly and ineffective. Membrane methods, especially reverse osmosis (RO), remove such pollutants better due to their selectivity and low energy requirements. RO membranes eliminate 158 pesticides [44]. Membrane technologies reduce pollutants and protect health [103]. These systems produce less sludge, are scalable, adaptable, eco-friendly, and efficient when used with other treatment procedures [45]. Membrane technology is essential to sustainable and cost-effective water and wastewater management. Membrane methods may be scaled up, adapted to different environments, and linked with other treatment processes to improve removal. Industrial activities release volatile organic compounds (VOCs) like solvents, chemical intermediates, and petroleum derivatives into wastewater. Polycyclic aromatic hydrocarbons (PAHs) from incomplete fossil fuel combustion and pharmaceuticals and personal care products (PPCPs) such hormones, antibiotics, and scents pose environmental hazards [46].

Fouling by extracellular polymeric substances (EPS), notably the carbohydrate-rich percentage of soluble microbial products, is a serious operational issue in membrane bioreactors (MBRs). Fouling can be chemically or physically removed. Optimising bioreactor condition, hydrodynamic adjustment, and module design can reduce fouling [47]. Reverse osmosis (RO) rejects ions, bacteria, and organic molecules across a semi-permeable membrane, making it unique among membrane processes [48].

5. Zero liquid discharge

Wastewater reuse and recycling are needed due to rising freshwater demand. Water is conserved and valuable resources are recovered. This method follows the EU circular economy model [49, 50]. Due of brine discharge's environmental impact, new laws have necessitated more sustainable treatment technologies. Zero Liquid Discharge (ZLD) systems are a major approach for recovering freshwater and reducing or eliminating liquid waste [51, 52]. ZLD uses modern desalination and treatment technology to create industrial and domestic high-purity water. Solid waste, mostly salts, can be recycled, sold, or used in other industries. ZLD systems can separate high-purity salts instead of mixed waste when optimized. Figure5 showed zero-liquid-discharge benefits.

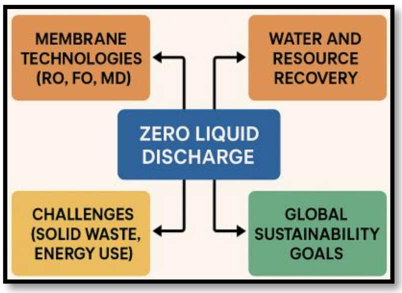

Figure5. Represents the benefits of zero liquid discharge

For water salinity control, power stations near the Colorado River employed ZLD in the 1970s [48,49]. ZLD adoption is highest in the US, especially in electricity. ZLD reduces boron pollution at the Illinois Dallman Power Plant's FGD wastewater treatment [59]. Mickley found that over 60 of 82 ZLD units supplied the electricity industry in 2008, with others in mining, chemicals, fertilizers, and electronics. The global ZLD market is expected to expand 12.1% from 2018 to 2026, from USD 0.71 billion to USD 1.76 billion [50]. Arvind Envisol (India), Toshiba (Japan), Veolia (France), Fluence, SafBon, Aquarion, and Lenntech are leading companies. The U.S., Middle East, Australia, Canada, Mexico, and the EU employ ZLD due to environmental legislation and water scarcity [53, 54]. The U.S. EPA has modified thermal power plant wastewater discharge laws to limit toxic metals and hazardous contaminants for the first time. These guidelines recommend Zero Liquid Discharge (ZLD) for flue gas mercury control, fly ash transport, and bottom ash transport effluents [55]. Power plants meeting these tighter limitations may receive regulatory incentives. ZLD is also being used in inland desalination facilities to handle brine. ZLD allows brackish water desalination in arid places since it uses less energy than saltwater. The U.S. Bureau of Reclamation and California Energy Commission have investigated ZLD applications in Arizona, California, Colorado, Nevada, and Texas [56, 57]. Water contamination and demand have increased in China due to rapid urbanization and industrialization. The Chinese government responded with a national water pollution action plan to enhance water quality and ecosystem health by 2020 [58]. Water recycling and stricter pollution control promote Zero Liquid Discharge (ZLD) in this approach. The coal-based power industry, which generates over 70% of China's electricity, drives the ZLD market [59]. ZLD is crucial at the energy–water nexus because 65–84% of major state-owned thermal power facilities are in water-scarce regions [60]. ZLD use is rising with the building of the world's first Forward Osmosis (FO)-based ZLD system at the Changxing coal-fired plant in Zhejiang Province. China's coal-to-chemicals industry, which transforms coal into fuels and chemicals, increases ZLD demand, especially in desert regions like Inner Mongolia, to conserve freshwater and protect ecologically sensitive zones [55].

5.1 Resource recovery and zero liquid discharge

Wastewater is becoming a profitable resource due to rising worldwide energy and water needs and costs. Reusing and recycling wastewater conserves freshwater. Important elements like phosphorus can be gathered and utilized as fertilizers. Treatment facilities can generate heat and power from wastewater organics [51].

5.2 Importance of the ZLD system for resource recovery

Industrial operations threaten freshwater, which is becoming more valuable. Industrial wastewater pollutes ecosystems and limits water supply [52]. Due to rising freshwater use and wastewater disposal constraints, water resource recovery technologies are implemented [63]. For wastewater disposal, rising treatment costs, and environmental awareness, Zero Liquid Discharge (ZLD) technologies have proven beneficial. These technologies assist enterprises meet environmental criteria, preserve water, and lower wastewater disposal expenses. ZLD systems reduce waste, recover resources, and efficiently treat industrial effluents, reducing waterway damage [54]. Lux Research predicts that rising water prices and strict environmental laws will spur ZLD industry technology developments. ZLD systems, which prevent power plant and industrial wastewater discharge, are predicted to rise 12% annually to $2.7 billion by 2030 [64].

Following **Figure6** indicated the importance of zero liquid discharge.

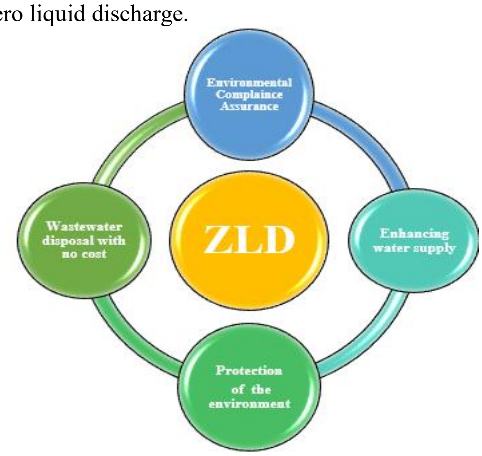

Figure6. Represents the importance zero liquid discharge

5.3. ZLD systems for resource recovery

Advanced Zero Liquid disposal (ZLD) systems capture and reuse practically all water and precious resources from industrial effluents to eliminate liquid waste disposal. Several ZLD systems use resource recovery to make them more sustainable and profitable [65].

5.3.1. Thermal ZLD system

A Zero Liquid Discharge (ZLD) system includes wastewater pretreatment, brine concentration, crystallization, evaporation, and solids recovery. Pretreatment include filtering, pH correction, de-aeration, and anti-scalants to reduce scaling potential and prepare the effluent for downstream concentration. A brine concentrator concentrates the water after pretreatment, removing a lot of it as clean distillate. In a brine crystallizer, dissolved solids are crystallized and water is evaporated from the remaining high-salinity brine. Solid leftovers are either collected as valuable byproducts (e.g., salts or metals) or disposed of in evaporation ponds or secure landfills. High-purity distillates from the concentrator and crystallizer are recycled back into the process as clean water, closing the loop [66].

5.3.2. RO-integrated with thermal ZLD

A reliable pressure-driven desalination process, reverse osmosis (RO), is typically coupled with thermal ZLD systems to increase efficiency. This hybrid method considerably reduces brine load in energy-intensive crystallizers and concentrators. RO uses only 2 kWhe/m³ for 50% seawater recovery, significantly less than thermal techniques. RO reduces thermal treatment capital and operating expenses by pre-concentrating wastewater. Secondary RO cuts brine treatment costs by 48–67% and energy use by 58–75% compared to brine concentrators and evaporation ponds in inland desalination. Modular membranes ease ZLD incorporation and growth. ZLD systems are useful but harmful to the environment. Leaking, stinking evaporation pond waste damages wildlife[67, 68].

5.3.3. Environmental impact of ZLD

Solid waste management is a problem. Solid residues in evaporation ponds can leak leachate, stink, and harm animals. Pollution prevention requires impermeable liners and advanced monitoring [69].

ZLD processes are energy-intensive and emit greenhouse gases (GHG) in addition to solid waste issues. Pretreatment processes like acidification and degasification release CO_2 from feedwater into the atmosphere. Using electrodialysis (ED) to concentrate RO brine increases energy consumption and CO_2 emissions, although being important for scale control. Life-cycle assessment studies show that replacing imported water with inland brackish water reverse osmosis (BWRO) systems in California can increase GHG emissions by 50%, emphasizing the need to balance sustainability goals with environmental trade-offs[70].

Following **Figure7** indicated the zero liquid discharge with resource recovery.

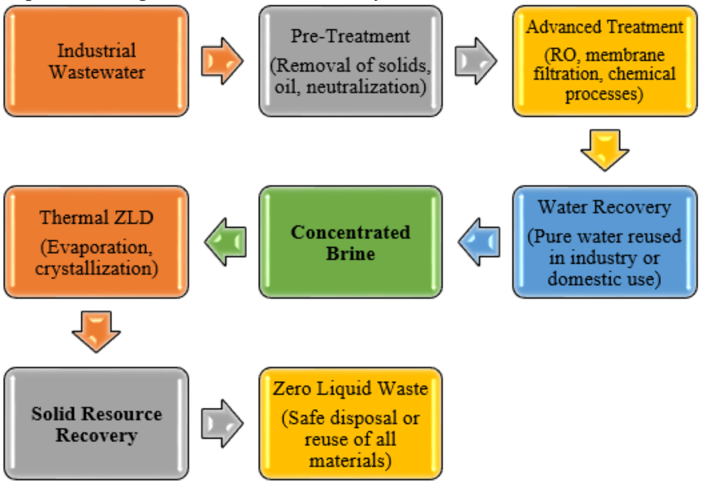

Figure7 Represents the zero liquid discharge with resource recovery.

6. Industrial water effluent

Global development has relied on economic expansion since the industrial and technological revolutions. Industrial pollution is now a major problem for environmental groups. Major civilizations were founded along rivers because water was crucial. Industrialization and globalization have increased water consumption, contaminating surface and groundwater. Humans depend on it everyday. The growing contamination of water bodies threatens life [71]. River water contamination has skyrocketed since industrialization. River-dependent communities have switched to groundwater due to water quality issues. Surface waters have lost aesthetic and ecological value due to overuse. Water is irreplaceable, thus this is frightening. Industrial effluents contain heavy metals, petroleum hydrocarbons, chlorinated compounds, acids, alkalis, dyes, and other harmful substances that damage water quality. Discharging such trash into aquatic environments without treatment causes severe environmental damage [72]. Industrialization—the transition from rural to industrial—is important to modernity. It boosts innovation, social transformation, and economic prosperity. Industrial development provides fertilizers, insecticides, and herbicides to enhance agricultural productivity, advancing a nation. Capital shortages impede India's economic growth. Industrial growth and trade increase when earnings are reinvested. Water contamination is a serious issue. Sewage, agricultural runoff, industrial effluents, septic tank waste, and stormwater runoff pollute water. Water becomes unsafe for ingestion and other uses when dangerous substances are released.

Although 70% of Earth is covered in water, just a small portion is useable. Rapid urbanization, agriculture, and industrialization have polluted critical waterways, endangering human and environmental health [73].

Surfactant wastewater is acidic, turbid, and organic-laden. Having a BOD_5/COD ratio above 0.75 suggests good biodegradability. Microfiltration with a 0.14 µm membrane greatly improved wastewater treatment, reducing turbidity by 99% (from 1300 to 17 NTU) and removing >93% of TOC, COD, BOD_5, and cationic surfactants. Industrial effluents, liquid production waste, are environmentally harmful. Indian rivers are polluted by uncontrolled discharge, affecting their physical, chemical, and biological qualities [74]. Molasses, alcohol, and chemical-rich effluents from Gorakhpur's Saraya Sugar Mill raise BOD, COD, suspended particles, and heavy metals. Sulphur dioxide and phosphoric acid in sugar manufacturing cause algal blooms and smells. Lignin-rich effluents from paper and pulp companies have high COD/BOD ratios, strong color, and suspended particles. Waterborne dioxins reach the human food chain and cause immunotoxicity, endocrine disruption, and cancer [75, 76]. The second-largest fertilizer consumer after China, India produces 80% of its urea. Effluents from the fertilizer sector contain ammonia, urea, and heavy metals. High pH and low DO make these effluents harmful to aquatic life. Temperature and pH affect the ratio of ionized and unionized ammonia in water, with the latter being more harmful.

Following **Table2** indicated the overview of industrial water effluent pollution.

Aspect	Details
Root Cause	Industrialization and technological advancement
Primary Water Sources Affected	Rivers, Lakes, Streams, Groundwater
Main Industrial Sources	Sugar Mills, Paper & Pulp Industries, Fertilizer Industries, Chemical Plants, Surfactant Manufacturing Units
Key Pollutants	Heavy Metals (Fe, Cu, Zn, Pb, Mn), Hydrocarbons, Chlorinated Hydrocarbons, Dioxins, Ammonia, Urea, Acids, Alkalies, Surfactants
Specific Byproducts (Examples)	Molasses, Alcohol (Sugar Mills); Lignin, Dioxins (Paper); Ammonia, Urea (Fertilizer)
Pollution Indicators	High BOD, COD, TOC, Suspended Solids, High Turbidity, Low DO, Foul Odor
Environmental Impacts	Algal Blooms, Water Discoloration, Loss of Biodiversity, Eutrophication, Bioaccumulation
Health Impacts	Immune suppression, Hormonal disruption, Cancer (via dioxins), Respiratory & Skin Disorders
Response to Contamination	Shift from river water to groundwater usage
Treatment Technology	Microfiltration (0.14 µm pore size), Biological Treatment, COD/BOD reduction, Regeneration Cycles
Treatment Efficiency	>93% removal of COD, BOD, TOC, surfactants; 99% turbidity reduction
Challenges	Rapid industrial expansion, Lack of proper waste treatment facilities, Point source pollution, Regulatory enforcement
Conclusion	Urgent need for regulation, advanced water treatment technologies, and sustainable industrial waste management practices

Table2. Represents the overview of industrial water effluent pollution

7. Membrane Technology for Water Recovery

Water recovery from industrial effluents, municipal wastewater, and brackish water sources is highly effective and scalable with membrane filtration technology. Microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) use molecular weight, charge, and hydrophilicity to size-select pollutants. These pressure-driven systems precisely remove suspended particles, colloids, microbes, dissolved organic materials, and inorganic ions. Microfiltration and ultrafiltration minimize turbidity and biofouling, while nanofiltration and reverse osmosis remove low-molecular-weight organics and salts [77].

Following **Figure8** indicated the membrane technology for water recovery.

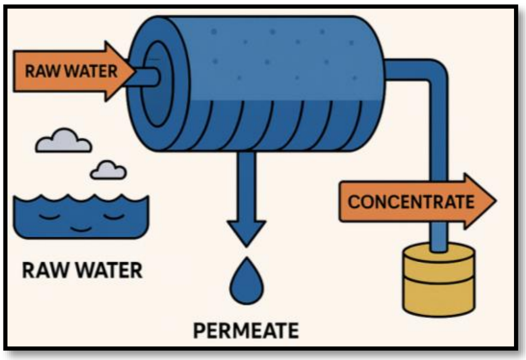

Figure8. Represents the membrane technology for water recovery

Membrane pore size, material chemistry, surface charge, hydrophilicity/hydrophobicity balance, trans membrane pressure (TMP), temperature, and cross flow velocity affect membrane water recovery efficiency. Advancements in membrane materials including TFC, ceramic, and nanomaterial-incorporated polymeric membranes (e.g., graphene oxide, TiO_2, ZnO, CNTs) have improved permeability, selectivity, antifouling performance, and chemical stability. Hydrophilic surface modifications or zwitterionic polymers can reduce organic and biofouling, extending membrane lifespan and flow [78].

The permeate recovery ratio (PR), which measures treated water recovery relative to feed, also affects water recovery performance. A greater PR saves water but might cause concentration polarization and membrane fouling if not regulated. Maintaining membrane performance requires backwashing, chemical cleaning (CIP), and periodic permeability restoration. Using hybrid technologies including membrane bioreactors (MBRs), advanced oxidation processes (AOPs), and forward osmosis (FO) can increase recovery rates and pollutant removal spectra [72].

Conclusion

Zero Liquid outflow (ZLD) systems reuse or convert wastewater into solid waste to eliminate liquid outflow. Modern ZLD systems selectively remove suspended particles, dissolved salts, and organic contaminants from industrial effluents using membrane-based RO, FO, MD, UF, and NF technologies. These methods recover salts, minerals, metals, and water efficiently. New membrane technologies, including hybrid systems and advanced materials like graphene oxide, carbon nanotubes, and metal oxide nanoparticles (e.g., TiO_2, ZnO), improve permeability, selectivity, fouling resistance, and energy efficiency.

Textile, pulp and paper, fertilizer, and sugar mill effluent with high COD/BOD, turbidity, surfactants, lignin, dioxins, and heavy metals is treated successfully by ZLD systems. Salt rejection and final polishing require RO and NF membranes, whereas membrane microfiltration removes 93% of organic and surfactant loading and 99% of turbidity. ZLD deployment demands effective solid waste and brine management, high capital and operational costs, and significant energy use. They can be solved by using renewable energy sources like solar-assisted MD or FO, improved cleaning procedures, and thermal or crystallization brine volume minimization. In water-scarce and cost-sensitive regions, Minimum Liquid Discharge (MLD) systems aim for 70–95% recovery to reduce discharge volumes and costs. ZLD and MLD frameworks are vital for linking industrial water use to sustainability and circular economy goals as global water scarcity rises and environmental rules tighten. Membrane-driven ZLD systems offer a technologically possible way to reuse all water and meet environmental and regulatory requirements in industrial wastewater treatment.

Future Perspective

Cost-effective, energy-efficient membrane systems with circular economy concepts are the future of Zero Liquid Discharge (ZLD). Flexible system designs and low-cost, high-performance membranes will make small and medium industries more accessible. ZLD, renewable energy, and industrial waste heat reduce energy needs. Policymakers can increase adoption with incentives and subsidies. Recovery of salts, fertilizers, and metals will lower operational costs and make ZLD a sustainable industrial water management leader.

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References

[1] Panagopoulos, A., & Michailidis, P. (2025). Membrane Technologies for Sustainable Wastewater Treatment: Advances, Challenges, and Applications in Zero Liquid Discharge (ZLD) and Minimal Liquid Discharge (MLD) Systems. *Membranes*, *15*(2), 64.

[2] Judd, S. J. (2017). Membrane technology costs and me. *Water research*, *122*, 1-9.

[3] Yaqub, M., & Lee, W. (2019). Zero-liquid discharge (ZLD) technology for resource recovery from wastewater: A review. *Science of the total environment*, *681*, 551-563.

[4] M. Arsalan, S. Imteyaz, M. Zeeshan, Rafiuddin, Synthesis, characterization, and electrochemical observation of PVC-supported strontium tungstate inorganic precipitated composite membrane, *Desalination and Water Treatment* 57 (2016). https://doi.org/10.1080/19443994.2015.1080191.

[5] Jahan, N., Tahmid, M., Shoronika, A. Z., Fariha, A., Roy, H., Pervez, M. N., & Islam, M. S. (2022). A comprehensive review on the sustainable treatment of textile wastewater: zero liquid discharge and resource recovery perspectives. *Sustainability*, *14*(22), 15398.

[6] M. Arsalan, M. Zeeshan, Rafiuddin, Comparison of physicochemical and electrochemical characterization of PVC incorporated ZT and ZM composite membranes and their applicability on TMS theoretical equation, *Journal of Molecular Structure* 1098 (2015). https://doi.org/10.1016/j.molstruc.2015.05.049.

[7] Tong, T., & Elimelech, M. (2016). The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. *Environmental science & technology*, *50*(13), 6846-6855.

[8] Obotey Ezugbe, E., & Rathilal, S. (2020). Membrane Technologies in Wastewater Treatment: A Review. *Membranes*, *10*(5), 89.

[9] Issaoui, M., Jellali, S., Zorpas, A. A., & Dutournie, P. (2022). Membrane technology for sustainable water resources management: Challenges and future projections. *Sustainable Chemistry and Pharmacy*, *25*, 100590.

[10] Calabro, V., & Basile, A. (2011). Fundamental membrane processes, science and engineering. In *Advanced Membrane Science and Technology for Sustainable Energy and Environmental Applications* (pp. 3-21). Woodhead Publishing.

[11] M. Arsalan, Rafiuddin, Synthesis, structural characterization, electrochemical, and electrical study of polystyrene-based manganous tungstate composite cation exchange membrane, *Desalination and Water Treatment* 52 (2014). https://doi.org/10.1080/19443994.2013.831793.

[12] Othman, N. H., Alias, N. H., Fuzil, N. S., Marpani, F., Shahruddin, M. Z., Chew, C. M., ... & Ismail, A. F. (2021). A review on the use of membrane technology systems in developing countries. *Membranes*, *12*(1), 30.

[13] Obotey Ezugbe, E., & Rathilal, S. (2020). Membrane technologies in wastewater treatment: a review. *Membranes*, *10*(5), 89.

[14] M. Arsalan, A. Zehra, M.M.A. Khan, Rafiuddin, Preparation and characterization of polyvinyl chloride based nickel phosphate ion selective membrane and its application for removal of ions through water bodies, *Groundwater for Sustainable Development* 8 (2019) 41–48. https://doi.org/10.1016/j.gsd.2018.06.008.

[15] Al Aani, S., Mustafa, T. N., & Hilal, N. (2020). Ultrafiltration membranes for wastewater and water process engineering: A comprehensive statistical review over the past decade. *Journal of Water Process Engineering*, *35*, 101241.

[16] Korenak, J., Basu, S., Balakrishnan, M., Hélix-Nielsen, C., & Petrinić, I. (2017). Forward osmosis in wastewater treatment processes. *Acta chimica slovenica*, *64*(1), 83-94.

[17] Qamruzzaman, A. Nasar, Treatment of acetamiprid insecticide from artificially contaminated water by colloidal manganese dioxide in the absence and presence of surfactants, RSC Adv. 4 (2014) 62844–62850. https://doi.org/10.1039/c4ra09685a.

[18] Wang, C., Wang, Y., Qin, H., Lin, H., & Chhuon, K. (2020, November). Application of microfiltration membrane technology in water treatment. In *IOP conference series: earth and environmental science* (Vol. 571, No. 1, p. 012158). IOP Publishing.

[19] M. Arsalan, M.A. Khan, F. Alam, M. Oves, PVC-supported SP composite membrane: its synthesis, physicochemical, and electrochemical characterization, *Journal of Solid State Electrochemistry* 21 (2017). https://doi.org/10.1007/s10008-017-3646-8.

[20] Qamruzzaman, A. Nasar, Kinetics of metribuzin degradation by colloidal manganese dioxide in absence and presence of surfactants, Chem. Pap. 68 (2014) 65–73. https://doi.org/10.2478/s11696-013-0424-7.

[21] Kafle, S. R., Adhikari, S., Shrestha, R., Ban, S., Khatiwada, G., Gaire, P., ... & Tiwari, A. (2024). Advancement of membrane separation technology for organic pollutant removal. *Water Science & Technology*, *89*(9), 2290-2310.

[22] Lee, K. P., Arnot, T. C., & Mattia, D. (2011). A review of reverse osmosis membrane materials for desalination—Development to date and future potential. *Journal of membrane science*, *370*(1-2), 1-22.

[23] Comparison of Membrane-based Solutions for Water Reclamation and Desalination

[24] Qamruzzaman, A. Nasar, Degradation of tricyclazole by colloidal manganese dioxide in the absence and presence of surfactants, J. Ind. Eng. Chem. 20 (2014) 897–902, https://doi.org/10.1016/j.jiec.2013.06.020.

[25] A. Nasar, Utilization of tea wastes for the removal of toxic dyes from polluted water—a review, Biomass Convers. Biorefinery. 13 (2023) 1399–1415, https://doi.org/10.1007/s13399-020-01205-y.

[26] Obotey Ezugbe, E., & Rathilal, S. (2020). Membrane technologies in wastewater treatment: a review. *Membranes*, *10*(5), 89.

[27] Carolin, C. F., Kumar, P. S., Saravanan, A., Joshiba, G. J., & Naushad, M. (2017). Efficient techniques for the removal of toxic heavy metals from aquatic environment: A review. *Journal of environmental chemical engineering*, *5*(3), 2782-2799.

[28] Gonzalez, A., Grágeda, M., & Ushak, S. (2017). Assessment of pilot-scale water purification module with electrodialysis technology and solar energy. *Applied Energy*, *206*, 1643-1652.

[29] Millar, N., McLaughlin, E., & Börger, T. (2019). The circular economy: swings and roundabouts?. *Ecological economics*, *158*, 11-19.

[30] Ismail, A. F., & Matsuura, T. (Eds.). (2016). *Membrane technology for water and wastewater treatment, energy and environment*. CRC Press.

[31] Jenkins, S., Paduan, J., Roberts, P., Schlenk, D., & Weis, J. (2012). Management of brine discharges to coastal waters recommendations of a science advisory panel. *Mesa, CA, USA: Southern California Coastal Water Research Project Costa*.

[32] Abualtayef, M., Al-Najjar, H., Mogheir, Y., & Seif, A. K. (2016). Numerical modeling of brine disposal from Gaza central seawater desalination plant. *Arabian Journal of Geosciences*, *9*, 1-18.

[33] Alnouri, S. Y., Linke, P., & El-Halwagi, M. M. (2018). Accounting for central and distributed zero liquid discharge options in interplant water network design. *Journal of cleaner production*, *171*, 644-661.

[34] Barrington, D. J., & Ho, G. (2014). Towards zero liquid discharge: the use of water auditing to identify water conservation measures. *Journal of cleaner production*, *66*, 571-576.

[35] Bazargan, A. (Ed.). (2022). *A multidisciplinary introduction to desalination*. CRC Press.

[36] Panagopoulos, A., Haralambous, K. J., & Loizidou, M. (2019). Desalination brine disposal methods and treatment technologies-A review. *Science of the Total Environment*, *693*, 133545.

[37] Mickley, M. (2008). *Survey of high-recovery and zero liquid discharge technologies for water utilities*. WateReuse Foundation.

[38] Yusuf, M. (2018). *Handbook of textile effluent remediation*. Jenny Stanford Publishing.
[39] Panagopoulos, A., & Haralambous, K. J. (2020). Minimal Liquid Discharge (MLD) and Zero Liquid Discharge (ZLD) strategies for wastewater management and resource recovery–Analysis, challenges and prospects. *Journal of Environmental Chemical Engineering*, *8*(5), 104418.
[40] Yaqub, M., & Lee, W. (2019). Zero-liquid discharge (ZLD) technology for resource recovery from wastewater: A review. *Science of the total environment*, *681*, 551-563.
[41] De Nicolás, A. P., Molina-García, Á., García-Bermejo, J. T., & Vera-García, F. (2023). Desalination, minimal and zero liquid discharge powered by renewable energy sources: Current status and future perspectives. *Renewable and Sustainable Energy Reviews*, *187*, 113733.
[42] Bornhoft, M., & Takach, P. (2018). Consideration for implementing a zero liquid discharge program. *Water technology*.
[43] Date, M., Patyal, V., Jaspal, D., Malviya, A., & Khare, K. (2022). Zero liquid discharge technology for recovery, reuse, and reclamation of wastewater: A critical review. *Journal of Water Process Engineering*, *49*, 103129.
[44] Tong, T., & Elimelech, M. (2016). The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. *Environmental science & technology*, *50*(13), 6846-6855.
[45] Durham, B., & Mierzejewski, M. (2003). Water reuse and zero liquid discharge: a sustainable water resource solution. *Water Science and Technology: Water Supply*, *3*(4), 97-103.
[46] Roberts, C. Effluent Limitations Guidelines and Standards for the Steam Electric Power Generating Point Source Category; Proposed Rule 78 Fed. Reg. 34,432 (June 7, 2013).
[47] Al-Karaghouli, A., & Kazmerski, L. L. (2013). Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews*, *24*, 343-356.
[48] Mickley, M. (2008). *Survey of high-recovery and zero liquid discharge technologies for water utilities*. WateReuse Foundation.
[49] Bond, R., & Veerapaneni, S. (2008). Zeroing in on ZLD technologies for inland desalination. *Journal-American Water Works Association*, *100*(9), 76-89.
[50] Burbano, A., & Brankhuber, P. (2012). Demonstration of membrane zero liquid discharge for drinking water systems: A literature review. *WERF 5T10*.
[51] Ranjan, A. (2018). China's water problems. *Asian Affairs*, *49*(4), 645-658.
[52] Jiang, Y. (2015). China's water security: current status, emerging challenges and future prospects. *Environmental Science & Policy*, *54*, 106-125.
[53] Finance, B. N. E. (2013). China's power utilities in hot water: Executive summary. *Bloomberg New Energy Finance*.
[54] Hopwood, D. (2014). Oasys applies FO to treat wastewater from China's growing power market. *Membr. Technol*.
[55] Xie, K., Li, W., & Zhao, W. (2010). Coal chemical industry and its sustainable development in China. *Energy*, *35*(11), 4349-4355.
[56] Minchener, A. J. (2011). Coal-to-oil, gas and chemicals in China. *IEA Clean Coal Centre*.
[57] Abdelhamid, A. (2015). *India uses zero liquid discharge (ZLD) to clean the Ganges River*.
[58] Tong, T., & Elimelech, M. (2016). The global rise of zero liquid discharge for wastewater management: drivers, technologies, and future directions. *Environmental science & technology*, *50*(13), 6846-6855.
[59] Nagai, K. (2010). Fundamentals and perspectives for pervaporation. *Comprehensive Membrane Science and Engineering*, 243-271.
[60] Zhang, Z., Xu, S., Wu, Y., Shi, S., & Xiao, G. (2021). Recent advances of pervaporation separation in dmf/h2o solutions: A review. *Membranes*, *11*(6), 455.
[61] Quiñones-Bolaños, E., Zhou, H., & Parkin, G. (2005). Membrane pervaporation for wastewater reuse in microirrigation. *Journal of Environmental Engineering*, *131*(12), 1633-1643
[62] Wijmans, J. G., Kaschemekat, J., Davidson, J. E., & Baker, R. W. (1990). Treatment of organic-contaminated wastewater streams by pervaporation. *Environmental progress*, *9*(4), 262-268.
[63] Elimelech, M., & Phillip, W. A. (2011). The future of seawater desalination: energy, technology, and the environment. *science*, *333*(6043), 712-717.
[64] Al-Karaghouli, A., & Kazmerski, L. L. (2013). Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews*, *24*, 343-356.
[65] Bond, R., Veerapaneni, S., Warner, J., & Roggensack, P. (2007). Zero liquid discharge for inland desalination.
[66] Bond, R., & Veerapaneni, S. (2008). Zeroing in on ZLD technologies for inland desalination. *Journal-American Water Works Association*, *100*(9), 76-89.
[67] Bond, R., Veerapaneni, S., Warner, J., & Roggensack, P. (2007). Zero liquid discharge for inland desalination.
[68] Burbano, A., & Brankhuber, P. (2012). Demonstration of membrane zero liquid discharge for drinking water systems: A literature review. *WERF 5T10*.
[69] Zhang, Y., Ghyselbrecht, K., Vanherpe, R., Meesschaert, B., Pinoy, L., & Van der Bruggen, B. (2012). RO concentrate minimization by electrodialysis: techno-economic analysis and environmental concerns. *Journal of Environmental Management*, *107*, 28-36.
[70] Chowdhary, P., Bharagava, R. N., Mishra, S., & Khan, N. (2020). Role of industries in water scarcity and its adverse effects on environment and human health. *Environmental concerns and sustainable development: Volume 1: Air, water and energy resources*, 235-256.
[71] Xu, X., Yang, H., & Li, C. (2022). Theoretical model and actual characteristics of air pollution affecting health cost: a review. *International Journal of Environmental Research and Public Health*, *19*(6), 3532.
[72] de la Casa, E. J., Guadix, A., Ibáñez, R., & Guadix, E. M. (2007). Influence of pH and salt concentration on the cross-flow microfiltration of BSA through a ceramic membrane. *Biochemical engineering journal*, *33*(2), 110-115.
[73] Miima, J. B., Neyole, E. M., Nyongesa, N. D., & Akali, N. M. (2011). Effluent Discharge by Mumias Sugar Company in Kenya: An Empirical Investigation of the Pollution of River Nzoia.
[74] Manivasakam, N. (1987). Industrial Effluents-Origin Characteristics, Effects. *Analysis and Treatment*.
[75] Jahan, S., & Singh, A. (2023). Causes and impact of industrial effluents on receiving water bodies: a review. *Malaysian Journal of Science and Advanced Technology*, 111-121.
[76] Ayyasamy, P. M., Yasodha, R., Rajakumar, S., Lakshmanaperumalsamy, P. K. S. M., Rahman, P. K. S. M., & Lee, S. (2008). Impact of sugar factory effluent on the growth and biochemical characteristics of terrestrial and aquatic plants. *Bulletin of environmental contamination and toxicology*, *81*, 449-454.
[77] Yadav, S. K. (2006). Human health implications due to water toxicity by pulp and paper mill. *Journal of Human Ecology*, *20*(2), 91-96.