The definitive publisher version is available online at 10.1016/j.desal.2023.117041

Electrodialysis desalination, resource and energy recovery from water industries for a circular economy

Mohammad Mahbub Kabir[1,2,3], *Golam Md. Sabur*[3], *Mst. Mahmoda Akter*[3,4], *Sang Yong Nam*[5], *Kwang Seop Im*[5], *Leonard Tijing*[1,2], *Ho Kyong Shon*[1,2] *

[1]*ARC Research Hub for Nutrients in a Circular Economy, School of Civil and Environmental Engineering, Faculty of Engineering and IT, University of Technology Sydney, P.O. Box 123, Broadway, NSW 2007, Australia.*

[2]*Center for Technology in Water and Wastewater, School of Civil and Environmental Engineering, Faculty of Engineering and IT, University of Technology Sydney, P.O. Box 123, Broadway, NSW 2007, Australia.*

[3]*Department of Environmental Science & Disaster Management, Noakhali Science and Technology University, Noakhali 3814, Bangladesh.*

[4]*School of Environmental Sciences, University of Guelph Ridgetown Campus, Ridgetown N0P 2C0, Canada.*

[5]*Department of Materials Engineering and Convergence Technology, Gyeongsang National University, Jinju, 52828, Republic of Korea.*

***Corresponding author**

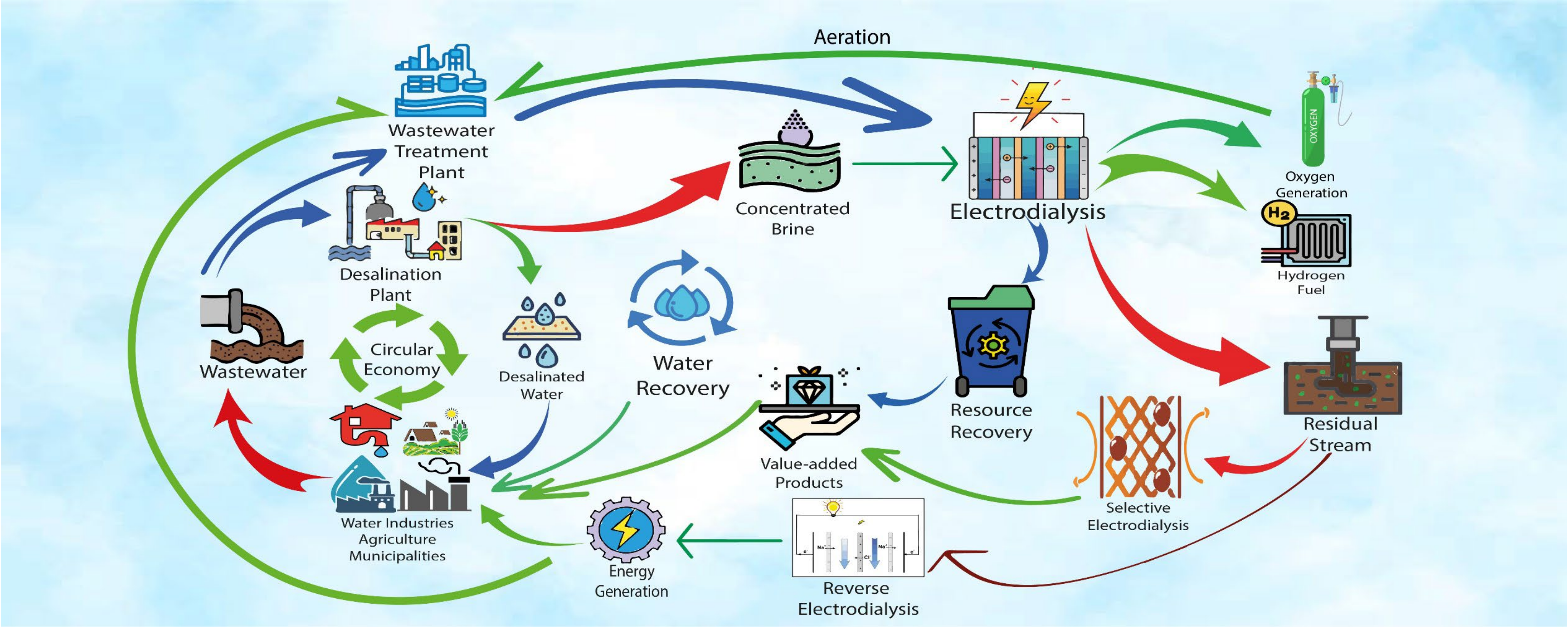
Email: Hokyong.Shon-1@uts.edu.au (H.K., Shon)

Abstract

The water industries (WIN) are now approaching towards sustainability of resource use, the recovery process, and water and energy management based on the circular economy (CRE) framework. Thus, the integration of electrodialysis (ED) technology in the WIN with a CRE paradigm should be recommended for ensuring the sustainability of ED desalination, resource, and energy recovery (EDDRR). According to the literature review, and to the best of our knowledge, there is no systematic study devoted to the sustainable EDDRR, hence a comprehensive and critical knowledge generation of EDDRR is essential for further technological advancements of ED. Thus, this review paper investigated the plausible incorporation of ED in the WIN for a CRE of EDDRR. The recent progress of EDDRR has been described comprehensively and critically. Moreover, an all-inclusive techno-economics and environmental sustainability analysis of EDDRR from WIN for a CRE has been carried out. The energy recovery techniques using ED were discussed critically. In addition, the latest case studies of EDDRR in the WIN have been discussed critically, and the significant scaling-up issues of EDDRR have been assessed based on the state-of-the-art recent scientific findings. Furthermore, some potential mitigation measures for the scaling-up issues have also been addressed. This study is the first comprehensive assessment of EDDRR from WIN for a closed-loop economy. The significant and novel insights of this study could be essential for the development of a sustainable CRE-based EDDRR process for WIN to attain sustainable development goals (SDGs).

Keywords: Water industries, circular economy, techno-economics, scaling-up issues, SDGs, energy recovery.

Graphical abstract



Nomenclature

AEL	Anion-exchange layer	SCP	Single-country publication
AEM	Anion exchange membrane	SDGs	Sustainable development goals
BA	Bibliometric analysis	SGP	Salinity gradient power
BM	Bipolar membrane	SGrE	Salinity gradient energy
BPMED	Bipolar membrane electrodialysis	TDS	Total dissolved solid
CEL	Cation-exchange layer	TGCS	Total global citation score
CEM	Cation exchange membrane	TLCS	Total local citation score
CEDI	Continuous electro-deionization	USA	United States of America
CON	Concentrate solution	VFA	Volatile fatty acid
CRE	Circular economy	WD	Water demand
DEDC	Decarbonized electrodialysis concentrate	WHO	World Health Organization
DIL	Dilute solution	WIN	Water industries
DROC	Decarbonized reverse osmosis concentrate	WWTP	Wastewater treatment plant
DWTP	Drinking water treatment plant		
ED	Electrodialysis		
EDDRR	Electrodialysis desalination and resource recovery		
EDI	Electro-deionization		
GHG	Greenhouse gas		
IEM	Ion exchange membrane		
IX	Ion exchange		
IXR	Ion exchange resin		
MCDI	Membrane capacitive deionization		
MCP	Multiple-country publication		
MREC	Microbial reverse-electrodialysis electrolysis cell		
MVA	Monovalent anion membrane		
MVC	Monovalent cation membrane		
MVM	Monovalent selective membrane		
MIT	Massachusetts Institute of Technology		
PV-ED	Photo-voltaic electrodialysis		
RED	Reverse electrodialysis		
RE	Renewable energy		
RO	Reverse osmosis		
RR	Resource recovery		

1. Introduction

Water plays a crucial role in the sustainable living of humans on Earth. However, with rapid industrialization, urbanization and increasing quality of life, this critical resource is facing extreme levels of contamination, which deteriorates the aquatic environment significantly. Water pollution reduces the proper ecosystem functioning and sustenance of living animals which ultimately affects socio-economic issues, environmental health crisis, and water shortage [1-6]. Accessible freshwater makes up less than 1% of the planet's water. It is best to avoid burdening freshwater usage, especially in areas where drinking water is difficult to attain. Almost 99%, or about 1.4 billion km^3, is seawater, which can be purified through desalination processes for various potable and drinking usage purposes [7]. The circular economy (CRE) concept has achieved great attention worldwide in the recent decade. The current linear economy (LE) practice of take-make-use-dispose pushed our society's requirement beyond the Earth's capacities. The CRE model seeks to redefine progress, focusing on constructive society-wide advantages. It entails gradually decoupling economic activity from consuming finite resources and designing waste out of the system [8-14].

Underpinned by a transition to sustainable development goals (SDGs), the circular model builds economic, natural, and social capital. It is based on three principles: design out waste and pollution, keep products and materials in use and regenerate biological systems. Water industries (WIN) are moving towards a vision of integrated resource recovery (RR) due to expanding sustainability and livability aspirations, operational challenges, network constraints, and emerging contextual factors [15-24]. Opportunities abound to apply CRE principles across water's roles as a resource, nutrient carrier, source of energy, and service. There is value in adopting a CRE approach for integrated water services for water utilities, society, and our natural environment. Water/wastewater desalination processes can be grouped into membrane-based processes and thermal processes. The membrane processes use membrane film as a barrier to separate the contaminants, while thermal desalination uses high energy for the vaporization of the potable water from the feed sources [25-32]. Electrodialysis (ED) and reverse osmosis (RO) are examples of membrane-based desalination technologies, whereas mechanical vapor compression (MVC), thermal vapor compression (TVC), multi-stage flash desalination (MSF), multi-effect evaporation/distillation (MED), and solar desalination systems are examples of thermal desalination.

However, ED and RO are the predominant membraned based desalination processes all over the world. Over the last 60 years, ED is considered one of the most suitable technologies for the desalination and recovery of valuable resources from sea water, brackish water, industrial wastewater, and municipal wastewater [33-37]. The main advantages of ED are higher water recovery rates compared to RO, easy operation, long membrane lifetime, operation at high temperatures, and unlike RO, it does not require extensive pre-treatment or post-treatment. Researchers studied the fundamental aspects as well as different development phases of ED technologies, i.e., continuous electro deionization, reverse electrodialysis, electrodialysis metathesis, selective electrodialysis and bipolar membrane electrodialysis systems. Besides, a bunch of ED technologies are still on a laboratory scale, and scaling-up issues are the major drawbacks of new variants of ED processes. Thus, the existing ED desalination capacity is only 4 % worldwide. However, to date, there are few fragmented research that reviewed ED technologies considering different technical issues, i.e., mathematical advancements for increasing ED separation and reduction of energy consumption [38-48], application of ED in various wastewater streams [49-53] and various aspects of IEMs [54-57]. According to the literature review, and to the best of our knowledge, there is no systematic study concerning the sustainability of ED desalination and resources recovery (EDDRR), hence a comprehensive and critical knowledge generation of sustainable EDDRR is essential for further technological advancements of ED. Nonetheless, as WINs are approaching towards sustainability of its resources use and recovery process, the application of CRE concepts in WINs should be considered vital for the SDGs, especially SDG 6: clean water and sanitation, SDG 7: affordable and clean energy, SDG 9: industries innovation infrastructures and SDG 13: climate action. Thus, integration of ED in the WINs for a CRE is a must for ensuring sustainable EDDRR and water resource management.

This review paper hence investigated the plausible applications of ED in the WINs for a CRE framework. The recent progress of EDDRR has been described comprehensively and critically. Moreover, an all-inclusive techno-economics and environmental sustainability analysis of EDDRR from WIN for a CRE has been carried out. In addition, the latest case studies of EDDRR in the WIN have been discussed critically, and the significant scaling-up issues of EDDRR have been assessed based on the state-of-the-art recent scientific findings. Furthermore, some potential mitigation measures for the scaling-up issues have also been addressed. This study is the first comprehensive assessment of EDDRR from WIN for a closed-loop economy. The significant insights of this study could be essential for the development of a sustainable CRE-based EDDRR process for the WIN.

2. Electrodialysis desalination, resource, and energy recovery for a circular economy.

The water industry (WIN) encompasses a wide range of sectors and activities, employing diverse technologies and disciplines to ensure the sourcing, treatment, distribution, management, development, and sustenance of water resources. Examples of WIN includes WWTP, DWTP, municipal wastewater treatment plant, water utilities, irrigation and agriculture, metallurgical industries, food and beverage industry, mining industry, chemical industries, electroplating industry, water desalination plants, etc [7]. Electrodialysis provides an opportunity to extract resources from wastewater and spent streams generated by various WIN. Such streams often contain contaminants and valuable components, presenting a significant potential for a CRE. CRE is an approach that maximizes the opportunity to depart away from the traditional perspective of "take-make-dispose" pattern by closing down the flow of resources creating a loop-like pattern that emphasizes on the reduction of resource use, conservation, sustainability of resource to build a future-proof resilient economy. However, implementing CRE practices poses a techno-economic challenge. The reuse, recycling, and recovery of materials in the water industries could open up the possibility to shift away from the older perspective of the linear economy to the newer closed-loop economy [58]. Many WIN have successfully used electrodialysis to recover nutrients, water, salts, metal ions, and even energy [42,59-60]. This technology represents a promising avenue for recovering valuable resources and reducing waste in the WIN.

2.1 Nutrients recovery using ED technologies

Effluents from wastewater treatment plants (WWTPs) often contain high levels of nutrients, which can lead to eutrophication and pose a threat to drinking water supplies if left untreated [61,62]. ED is more energy efficient in terms of recovering useful nutrients from wastewater [62]. Using ED, WIN could selectively recover nutrients products like ammonia and phosphorus [62]. The increasing global demand for food has created concerns about the sustainable availability of natural fertilizers [61]. More and more fertilizers used in agricultural fields have created a heavy burden for WWTPs [63].

Applying too much fertilizer for whatever purpose could possibly pollute water sources and contribute to the emission of greenhouse gases [64]. A significant number of studies have been made on the recovery of nutrients from wastewater via ED. A recent study on nitrate removal and recovery from municipal wastewater was able to come up with the conclusion that nutrients like NO_2^- can be recovered using multi-batch ED methods in different conditions of concentration, flowrate, and dilute-to-concentrated volume ratio [61]. The WWTP at the municipal scale can be a viable source to extract nutrients via ED. Several studies were made on the recovery of nutrients from municipal wastewater sources. Such instances can be observed in the study of Oliveira et al. [65], who studied on recovering phosphorus and nitrogen from municipal solid waste digestate using combined independent processes of ED and gas permeable membrane. They successfully extracted 81% of phosphorus and 74% NH_4^+. Also Kedwell et al. [66] used SED to retrieve 72% ammonium and 90% phosphate from municipal wastewater.

Alkaline ammonium stream from WWTP was used as feed and ED combined with liquid-liquid membrane contactors was used to recover ammonium [67]. Liu et al. [62] conducted a study on SED to isolate and reclaim nitrogen and phosphorus during the desalination of secondary effluent treatment. Another research on resource recovery by selective electrodialysis led by Ye et al. [68] was able to recover nutrients such as PO_4^{3-}, SO_4^{2-}, NH_4^+, K^+, $Mg^{2+,}$ and Ca^{2+} from swine wastewater.

They were able to fractionate and separate anions and cations. Mondor et al. [64] showed excess nitrogen in intensive animal production could be concentrated with ED and this concentration is similar to the reverse osmosis concentrate suggesting that ED was more effective in particular nutrient recovery even though RO required more energy. Other than the desalination of wastewater from various sources, urine is also used as feed in ED to conduct nutrient recovery experiments. For instance, a study conducted by De Paepe et al. [69] was able to extract SO_4^{2-}, K^+, and NO_3^- from human urine added with demineralized water to simulate flush water using an installation combined of ED, nitrification, and precipitation. Wang et al. [70] were able to recover 65% and 54.9% phosphate and sulphate, respectively from source-separated urine by SED in the electrodialysis membrane bioreactor (EDMBR). The urine stream delivers a significant amount of nutrients from homes (81% N, 50% P, and 55% K), but less than 1% of the overall volume of municipal wastewater [63]. This could open up a new dimension in municipal WWTPs from where nutrients can be recovered which would contribute to sustainable resource management [70].

A lab-scale integration of BPMED and MCDI led by Gao et al. [71] showed greater recovery of nutrients as well as the potentiality of ED paired with other membrane techniques to recover nutrients from wastewater streams. Shi et al. [72] carried out research using a laboratory-scale BPMED to extract nutrients from both synthetic and real pig manure. They achieved a nutrient recovery rate of 78% for NH^{4+}, 75% for PO_4^{3-}, and 87% for volatile fatty acids (VFAs). The findings of their study established the viability of utilizing two-stage BMED technology for the retrieval of nutrients from pig manure. Shi et al. [73] made recovery of NH_4^+ from synthetic wastewater using different types of BPMED. Another pilot scale ED paired pilot reactor was able to demonstrate recovery of concentrated product of nutrients (NH_4-N=7100 mg/L and K= 2490 mg/L) from wastewater which is suitable as fertilizer [74].

The waste products generated by various industries could also be utilized as a source for extracting valuable nutrients using ED. Barros et al. [75] used monoselective cationic membrane and non-monoselective membrane ED to recover K^+, Ca^{2+}, and Mg^{2+} from distillery vinesse. A similar ED method was operated to recover SO_4^{2-}, PO_4^{3-}, NO_3^-, and HCO^{3-} from the salt concentrate from reverse osmosis processes. Table 1 illustrates the various nutrients recovered by ED system in the literature including feed water and specific ED techniques.

Table 1 Nutrients recovery from WIN using ED for a CRE.

Feed sources	ED techniques	Materials Used	Recovered nutrients	Performance	Flow rate	Voltage	References
Synthetic secondary effluent	SED	CEM: Neosepta CMX, AEM: Neosepta AMX, MVA: Neosepta ACS	NO_3^- and PO_4^{3-}	40.64 mg N L^{-1} 21.2 mg P L^{-1}	8 mL/min, 16 mL/min	9 V, 15 V	[62]
Municipal wastewater and synthetic wastewater	Single and multi-batch ED	CEM: Ralex CM-PES, AEM: Ralex AM-PES	NO_3^-	19.2 mg/L	60 Lh^{-1}	1-10 V; 1V/cell pair	[61]
Swine manure	ED with RO	AEM: AMX, AMX-SB, AR103 QDP, CEM: CMX, CMB, Cation 164 LMP	NH_3	16g/L	-	1V/membrane	[64]
Swine wastewater	SED	PC-SA, PC-SK, PC-MVK, PC-MVA, PC-SC	PO_4^{3-}, SO_4^{2-}, NH_4^+, K^+, $Mg^{2+,}$ and Ca^{2+}	PO_4^{3-}: 58.4 mg/L, SO_4^{2-}: 146.0 mg/L, NH_4^+: 837.6 mg/L, K^+: 307.0 mg/L, Mg^{2+}: 64.4 mg/L, Ca^{2+}: 119.2 mg/L	10.62 cm/s	7.8 V	[68]
Human urine	SED	CEM: Neosepta CMX, AEM: Neosepta ACS, AEM: Neosepta AMX	PO_4^{3-} and SO_4^{2-}	PO_4^{3-}: 27 & 19 mg/L, SO_4^{2-}: 134.1 & 118 mg/L	0.5 m^3/h	0.43 ± 0.12 V. 0.11 ± 0.03 V	[70]
Model Wastewater	Laboratory-scale ED	AEM & CEM: RALEX	Phosphorus	96.01-98.99%	-	14 V	[76]

Treated wastewater and synthetic wastewater	BPMED and MCDI	CEM: Neosepta CMX, AEM: Neosepta AMx, BM: Fumasep FBM	NH_4^+-N, PO_4^{3-} and P	NH_4^+-N: ~77%, PO_4^{3-}: 89%,	BPMED: 50 mL/min, MCDI: 3.5 mL/min	0.8-1.4 V	[71]
Pre-treated Wastewater	Pilot scale ED	CEM: General Electric CR67, AEM: General Electric AR204SZRA	NH_4^+-N, K^+	NH_4^+-N: 7100 ± 300 mg/L, K^+:2490 ± 40 mg/L	1250 mL/min	~18-38 V	[74]
Municipal solid waste digestate	ED combined with gas-permeable membranes	CEM: CR67R, AEM: AR204R	Phosphorus and nitrogen	P: 81%, NH_4^+: 74%	-	-	[65]
Alkaline ammonia stream from WWTP	ED combined with liquid-liquid membrane contactors	CEM: Fujifilm Type 2, AEM: Fujifilm Type 2	$(NH_4)_3PO_4$, NH_4NO_3	$(NH_4)_3PO_4$:15.6 ± 0.9%, NH_4NO_3:14.7 ± 0.6%	-	7.5 V	[67]
Synthetic wastewater	Different types of BMPED	IEM: Polyethylene heterogeneously (MemBrain)	NH_4^+	16 g/L	300 mL/min	Below 60 V	[73]
Vinasse from distillery	Monoselective cationic membrane and non-monoselective membrane	MVM: Neosepta from ASTOM co., CEM: HDX from Hidrodex	K^+, Ca^{2+} and Mg^{2+}	K: 66%, 72%, 44%, 72% Ca: 83%, 68%, 48%, 59% Mg: 32%, 1.2%, 26%, 47%	-	-	[75]
Synthetic and real pig manure	Laboratory scale BPMED	CEM, AEM, BM: MemBrain	NH_4^+ and PO_4^{3-}	NH_4^+:78%, PO_4^{3-}:75%	300 mL/min	60 V	[72]
Human urine	Pilot scale ED combined with precipitation and nitrification	AEM: PC-SA, CEM: PC-SK	SO_4^{2-}, K^+ and NO_3^-, PO_4^{3-}	SO_4^{2-}: 74%, K^+: 71%, NO_3^-: 70%, PO_4^{3-}: 40%	1 L/min	10 V	[69]

Municipal wastewater	SED	ED stack: ED-64-004, AEM and CEM: polyester MVM: Polyvinyl chloride	PO_4^{3-} and NH_4^+	NH_4^+: 72 ± 1%, PO_4^{3-}: 90 ± 10%	20 L/h	1.6 V drop per stack	[66]
Salts in reverse osmosis concentrate	Monoselective membrane ED and non-monoselective ED	CEM: PCA-SK, AEM: PC-SA & PC-MVA	SO_4^{2-}, PO_4^{3-}, NO_3^-, HCO^{3-} and Cl^-	SO_4^{2-}: 77-95% PO_4^{3-}:56-86% NO_3^-: 92-98% HCO^{3-}: 95% Cl^-: 96-98%	150 L/h	2 V for each cell pair, less than 10 V	[77]

CRE is the key to achieving sustainable development. Undoubtedly, the transition to a circular economy represents a significant solution to reduce the consumption of new raw materials and minimize waste production. In order to achieve this, WIN must seek out methods to effectively close their production loops. ED processes have proven to be highly effective, energy efficient, and environmentally friendly over the past few decades [78]. Continued improvements in the cost-effectiveness and efficiency of ED processes have the potential to facilitate the establishment of a CRE incorporating the WIN in the near future.

2.2. Energy generation from WIN for a CRE by electrodialysis techniques

As the demand for water increases and conventional sources become scarcer, alternative sources like desalination and water reuse are becoming increasingly crucial. However, the process of desalination consumes a considerable amount of energy and depends heavily on fossil fuels, which undermines its ability to be widely utilized and sustainable in the long run. The most effective solution is to transition towards low-emission renewable energy sources requiring minimal water [79]. Membrane-based ED is an effective method for water desalination and has recently garnered significant attention due to its usefulness to generate energy.

Over the past few decades, salinity gradient energy (SGrE), also known as blue energy, has gained significant interest as an alternative renewable energy source to generate electrical energy. Reverse electrodialysis (RED) is a technology capable of harnessing the potential of SGrE in river estuaries, converting it into electrical energy [80]. When two different concentrations of saltwater mix, it causes a release of free energy due to the difference in chemical potential between them. By controlling the mixing process, this energy can be harnessed by means of redox reactions, the ionic current can be converted into an electrical current, which can then be harvested if an external load is connected [79-81]. This produced electricity is termed salinity gradient energy (SGrE) [81].

RED technology also has the potential to be used in the production of hydrogen as a source of energy. Several lab-scale studies have been conducted using ED to produce hydrogen [7]. Numerous research studies have focused on different methods of hydrogen production from wastewater. Kabir et al. [7] critically studied the role of WIN in hydrogen production from a CRE perspective and came to conclude that in the pursuit of CRE hydrogen production can be the portal to achieve sustainability in WIN. The simultaneous production of hydrogen and neutralization of waste acid using RED technology from industrial wastewater streams is a promising method of energy generation within the WIN [82]. One major limitation of the RED technology when operated in an open-loop configuration is the lack of access to natural high-salinity water sources in areas with high power demand. However, this issue can be overcome by utilizing a closed-loop RED heat engine system, where specially formulated artificial saline solutions are used to increase the salinity gradient and improve the performance of the RED unit [83]. As the overabundant heat energy dissipated from various manufacturing industries cannot be used entirely for other purposes like district heating or on-site industrial use, the excess heat energy can be used to produce hydrogen from heat-driven RED technology and several studies have proven to be an economically feasible solution to generate hydrogen from waste heat using heat-driven RED [84]. The current state of the energy crisis and global warming highlights the urgent need to adopt renewable technologies, and every possible source of energy, including SGrE, should be given priority in our efforts to transition toward a sustainable future.

2.2.1 Electricity generation from RED technology

The utilization of SGrE represents a promising solution to address the challenges posed by the water-energy nexus, as it is a reliable and eco-friendly source of renewable energy. RED is currently considered the most viable method for harvesting SGrE among the proposed techniques [81]. RED is a developing electro-membrane technology that generates electrical energy by utilizing ion-exchange membranes to harness the chemical potential difference between two solutions of different concentrations [81]. In a RED stack, anion-exchange membranes and cation-exchange membranes are arranged in an alternating pattern to separate the concentrate and dilute salt solutions. Due to the difference in chemical potentials between the solutions, cations move toward the cathode, while anions move toward the anode. These ionic mobilities are then converted to electron transfer through oxidation-reduction reactions that occur at the electrodes. The transfer of electrons from the anode to the cathode through an external circuit generates an electrical current [47].

Theoretically, the influx of 1 m^3 of fresh water into the sea can yield around 0.8 kWh, which corresponds to approximately 2 TW of SGrE based on the total fresh water discharge of major rivers across the globe [85]. Previous studies have estimated the theoretical salinity gradient energy potential at river mouths to be 15,102 TWh per year, which is equivalent to 74% of the worldwide electricity consumption [81]. In addition to freshwater and seawater, other feed streams like treated wastewater effluents and desalination brine can also be utilized to expand the potential of salinity gradient energy. Furthermore, synthetic high-salinity draw solutions such as ammonium bicarbonate or sodium chloride have been studied for their ability to recover low-grade waste heat through a closed-loop osmotic heat engine and as a concentration battery for energy storage purposes.

Numerous scholars and researchers have conducted studies on the production of electricity from ED technology. They focused on improving the efficiency and economic viability of the process. The studies have provided valuable insights for optimizing the design and operating parameters of SGrE systems by integrating multidisciplinary perspectives in emerging economies. Furthermore, these insights can also aid in identifying promising sites for installing SGrE-based power plants in WIN [86-88]. A novel approach for water desalination, known as power-free ED was proposed. This method involves the integration of RED with conventional ED, utilizing the salinity gradient between the low and high salt concentration compartments to generate power. This power, in turn, is used to run the desalination process in the ED stack [89]. Jang et al. [90] assessed the future prospects and new developments in the prospects of RED for the generation of SGrE with a focus on ion exchange membranes (IEMs) and electrodes. They came to conclude that the optimization in the electrode system of IEMs may well facilitate the redox reaction and hence increase the production capacity of salinity gradient power plants.

According to a recent study, it is suggested that employing a suitable pre-treatment strategy to eliminate humic-like substances can effectively mitigate membrane fouling, thereby maintaining a high-power density during long-term operation of RED systems in natural water conditions [91]. A recent study found that a dual media filter could effectively remove suspended particles larger than 10 μm from water, providing a simple and effective pre-treatment approach for RED systems to harvest SGrE [80]. Research conducted by Long et al. [92] investigated the impacts of surface hydrodynamic slip modification on ion transportation for SGrE harvesting. Altıok et al. [47] investigated the operational parameters in RED and found that flow velocity and salinity ratio have the most significant impact on RED performance.

RED has made significant progress in fundamental research, experimental investigations, and field demonstrations aimed at improving stack design. Previous studies suggest the viability of integrating RED in WIN to generate electricity. For instance, Tristán et al. [79] suggested integrating up-scaled RED systems in seawater RO plants distributed worldwide. Atlas and

Suss [93], in their study, extended the theory of ED to include simultaneous desalination and electricity generation resulting from spontaneous redox reactions in their model. This novel approach may pave the way for designing next-generation systems in which desalination performance and energy efficiency can be significantly improved. A pilot-scale RED unit was installed in a chemical desalination water treatment plant to experimentally demonstrate the feasibility of simultaneous electricity generation alongside water treatment, utilizing highly mineralized liquid waste [94].

Although many studies have investigated the generation of electrical power from salinity gradient in the water industries, full-scale RED plants have not yet been established. Further pilot-scale studies are needed to validate the feasibility of electricity generation from WIN RED. At present, a project named REA Power is dealing with an innovative concept that utilizes RED technology to extract "osmotic energy" from two salt solutions that show a large difference in salt concentration, which is commonly known as salinity gradient power (SGP) [95]. This project could open up the future to sustainable development of energy. The importance of ED in the current energy crisis cannot be overstated. ED has immense potential and is increasingly being recognized for its value. In addition, there are ongoing efforts to improve the technology and several large-scale projects have already yielded promising results. Furthermore, ED has applications beyond water desalination, such as the RED heat engine.

Industrial sectors often produce more heat than necessary during the production process, resulting in a surplus of heat known as waste heat. In the WIN, low-grade (50-100 °C) heat energy can be harnessed for electricity generation. The RED heat engine is based on the idea that the efficiency and performance of electricity generation via RED can be improved by utilizing waste heat to fulfil the necessary heat requirements. This approach maximizes energy efficiency and helps to mitigate the impact of waste heat on the environment too. Also, low grade waste heat, which may not have significant other uses, can be converted to electric energy by using the RED heat engine [83]. The concept of CRE basically makes the production line a closed loop. While low-grade heat generated in WIN may have the chance to be wasted due to no other admissible utilization, the use of RED heat engine opens the gateway to use this energy, thus closing a section in the production system as RED heat engine uses suitable salt for the generation of energy. Generally, a suitable salt for such applications should have characteristics like high water solubility, high conductivity and large activity coefficients ratio [96]. Table 2 presents an overview of studies conducted on the generation of electricity through RED techniques.

Table 2 Electricity production from WIN for a circular economy using RED.

Used solution	*Membranes used*	*Active area*	*Thickness*	*Feed conc.*	*Flow rate & velocity*	*temperature*	*Power output Or density*	*Software used*	*Reference*
RO effluent	Fumasep FKS-50 CEM, Fumasep FAS-50 AEM	0.175 m^2 0.175 m^2	50 µm, 50 µm	2.0-0.5 M	3.0 cm/s	24 °C	2.56 W/m^2, 1.15 MW	Aspen Plus V11 (AspenTech)	[79]
NaCl solution of different conc.	Ralex AMH-PES, Ralex CMH-PES	100 cm^2	714 µm, 700 µm	NaCl: 1 g/L, 15 g/L, 30 g/L, 45 g/L	300 mL/min; 0.833 cm/s	25 °C	0.222 W/m^2	Design expert software v11.0.1 (STAT-EASE)	[47]
Artificial Seawater and river water	-	-	100 µm	High: 0.513 M, Low: 0.017	1 cm/s	25 °C	1.3 W/m^2	COMSOL Multiphysics 5.5	[86]
Synthetic Sea and River Water	AEM & CEM: Fujifilm Type 1	0.002 m^2	254 µm	30 & 1g/L, 36 & 0.06 g/L,	77 & 50 mL/min; 0.8 and 0.5 m/s	24 °C	1.3 MJ/m^3 & 1.6 MJ/m^3	Powersim Studio 10 Academic SR4	[87]
Seawater and treated wastewater effluent	CEM: PCSA, PCA GmbH; AEM: PCSK, PCA GmbH	64 cm^2	0.45 mm	-	107 mL/min; 0.99 cm/s	11-16 °C, 30-33 °C	94.4 ± 0.1 mW/m^2 (Nov), 247.5 ± 10.9 mW/m^2 (Jul); 137.9 ± 6.2 mW/m^2 (Jul), 10.4 ± 1.8 mW/m^2 (Sep)	-	[88]
NaCl solution, Simulated seawater and wastewater	CEM & AEM: Hefei ChemJoy Polymers	189 m^2	50 µm	Low: 1 g/L, 3 g/L; High: 10 g/L, 30 g/L, 70 g/L, 150 g/L	75 mL/min	-	-	-	[89]

Pre-treated freshwater and seawater	CEM & AEM: Fujifilm BE Series	100 cm^2	CEM: 45 µm, AEM: 53 µm	0.05M-0.5M NaCl	0.5 cm/s	-	0.16-0.17 W/m^2, 0.20-0.21 W/m^2	LAS 4.12, ZEN black, JEOL SEM V 7.07	[80]
Brackish water	-	-	127 µm	0.5-1 M	0.278 mm/s	25 °C	~42 mW/cm^2	COMSOL Multiphysics, direct solver MUMPS,	[93]
Process fluid of WTP	IONSEP-MC-A anionite membrane; IONSEP-MC-C cationite membrane	24 dm^2	0.42 mm	-	4.2 cm/s.	45 °C & 50 °C	0.36 W/m^2	-	[94]
Seawater and Brine	Fujifilm membrane	100 cm^2	-	0.1 – 1 M (dilute); 0.5 – 5 M (concentrate)	0.3-4 cm/s	20-40 °C	6 & 7 W/m2	Ansys CFX® 13, PSE gPROMS®	[95]
Brine	Fujifilm membranes	100 cm^2	150 mm	0.5-4.0 M NaCl	-	> 650 °C, 230-650 °C, 100-230 °C, < 100 °C	Exergetic efficiency of about 85%	GAMS v24.1	[96}
(NH$_4$)HCO$_3$ solution	Fujifilm Type 10; Fumasep F-10150-PF	0.1 x 0.44m^2	120 µm; 140-150 µm	0.05-2M	0.2 L/min	25 °C	~1.5 W/m^2	-	[97]
NH$_4$HCO$_3$ solutions	Fujifilm Type 10 membranes	0.25 m^2	-	0.01-2M	0.215 l/min	25 °C	2 W/m^2-5.7 W/m^2	Aspen plus® regeneration model	[98]

The RED heat engine is still being studied to achieve a future-proof and efficient performance. In a recent development, Giacalone et al. [97] successfully created a prototype of the RED heat engine, marking the first operational thermolytic RED heat engine. This prototype consisted of a RED unit, accompanied by a thermal regeneration unit, enabling the conversion of salinity gradient energy into electrical energy. The thermal regeneration unit served as a means of restoring the initial operating conditions of the feed streams by utilizing low-grade waste heat. Tamburini et al. [96] conducted a comparison of the RED heat engine with other heat engines, evaluating their qualitative viability in terms of exergetic efficiency. This study confirmed the RED heat engine's potential as one of the most promising heat-to-electrical energy converters for the future. Incidentally, WIN have the ability to generate a diverse range of salts or concentrated salt brines. Among them, certain salts possess thermal sensitivity. These salts can be the agent in producing electrical energy from low-grade waste heat generated in WIN. For instance, ammonium bicarbonate (NH_4HCO_3) is a good thermolytic salt, it can be used as a low-grade heat energy converter [83,96-98]. RED heat engine possesses immense promise as an innovative solution for harnessing SGrE effectively.

2.2.2 Hydrogen generation from WIN for CRE by electrodialysis technology

Green hydrogen is considered a suitable alternative to traditional fossil fuels. Green hydrogen is considered to have no carbon footprint because hydrogen is directly produced from water by the electrolysis of water molecules. Hydrogen is a potentially revolutionary energy carrier with the ability to significantly impact the global energy transition and reduce greenhouse gas emissions in the coming decades. Many theoretical and experimental pieces of research have been conducted on generating hydrogen from water industries by RED. As the concept of CRE deals with the maximization of resource usage, hydrogen production from industrial wastes provides an opportunity to establish CRE in WIN.

Recent studies have suggested the use of microbial reverse-electrodialysis electrolysis cells (MREC) in generating hydrogen from supplies of seawater and river water. It is a novel technology. Nam et al. [99] conducted research to demonstrate that ammonium bicarbonate salt regeneration can also generate hydrogen gas using MREC. They were able to achieve a maximum hydrogen production rate of 1.6 m^3 $H_2/m^3/d$ with a hydrogen yield of 3.4 mol H_2/ mol acetate. A comparable study has suggested that hydrogen gas can be generated through a single process by harnessing salinity-driven energy and organic matter degradation with the help of exoelectrogenic bacteria. They demonstrated that H_2 production increased from 0.8 to

1.6 m^3 of hydrogen gas per m^3 of analyte per day with seawater and river water flow rates ranging from 0.1 to 0.8 mL per minute [100]. Hidayat et al. [101] used insights from previous similar studies and tested the effects of the presence of monovalent and multivalent ions on the performance of MREC. The researchers concluded that the performance of MREC was negatively impacted by the presence of multivalent ions. Tang et al. [102] combined bipolar membrane electrodialysis and ethanol fermentation to produce hydrogen biologically. They achieved a hydrogen production rate of 2.2 mol H_2 per mole glucose, indicating that the separation of acetate from the fermentation system played a significant role in enhancing hydrogen production capacity. Exoelectrogenic bacteria were pre-acclaimed in anodes of ED system that achieved the maximum hydrogen production rate of 0.16 m^3 H_2/m^3 dilute.

A 20-modified cell pair RED stack was used at laboratory scale and this system was used for hydrogen production [103]. Nazemi et al. [104] developed a thermodynamic model for RED systems with a varying number of membrane pairs to predict the performance and were able to extract 0.95 kWh/m^3 as hydrogen energy. A laboratory-scale RED unit consisting of 27 cell pairs was utilized to produce hydrogen from synthetic alkaline polymer water. The study reported a maximum hydrogen production of 44 cm^3 per hour per cm^3 of electrode surface area [105].

Studies exploring the economic feasibility of hydrogen production from RED technology have indicated that a minimum production rate of 1.19 $mol/m^2/h$ is required for RED to compete economically with existing renewable technologies for hydrogen production [84]. Because, after all, economic viability plays a crucial role in all energy-related decisions. A laboratory scale ED system successfully produced hydrogen gas at the cathode compartment (Fig. 8) and the produced hydrogen had 98% purity. The hydrogen production could save 7% of total energy requirement in the ED system and further improvement of this system can open-up a new horizon of self-energy generating ED technology in future [106].

Hydrogen fuel has gained significant momentum recently and its potential as a low-carbon energy carrier has been researched extensively over the past few decades. Scientists worldwide have been focused on developing emission-free hydrogen production technologies, exploring transportation options, and creating storage facilities for hydrogen fuel to enable its use as a clean energy source [7]. Producing hydrogen is indeed a prerequisite for shifting to clean energy sources.

2.3. Metals and ions recovery from process water of WIN for a CRE by electrodialysis technology

Metals, metalloids, metal ions, and their salts can originate from various WIN. These substances, whether naturally occurring or introduced through human activities, pose a significant risk to ecosystems and human health. Heavy metals, in particular, have the potential to cause devastating consequences for humans, animals, and plants. Shockingly, approximately 2 million tons of untreated industrial, sewage, and agricultural waste are discharged into water bodies each year, exacerbating the contamination issue [107]. In fact, this amount has increased dramatically in recent years. The untreated wastes from various sources eventually cause the water to render harmful for various activities.

WIN employed ED techniques to treat saline water and brine. Recent studies regarding the desalination of water suggest that the treatment of metal-contaminated water gained immense interest with the advance of new technologies in ED. Particularly, SED is used to selectively separate metals. Metals like silver, chromium, nickel, mercury, zinc, cadmium, lithium, copper, magnesium, aluminum, to name but a few are removed from wastewater. For instance, lithium, a unique element on Earth, stands out as the most widely utilized material in electronic device batteries. A recent comprehensive review focused on lithium recovery processes assessed the potential and limitations of contemporary electro-membrane methods. The conclusion drawn in their review is that the application of Electrodialysis (ED) holds promise as a compatible approach to reducing recycling costs and energy consumption [108]. Other non-metal ions like arsenic and lead are also removed using ED [107]. A comprehensive outlook on the research studies on metals, ions and salt recovery by ED is listed in Table 3.

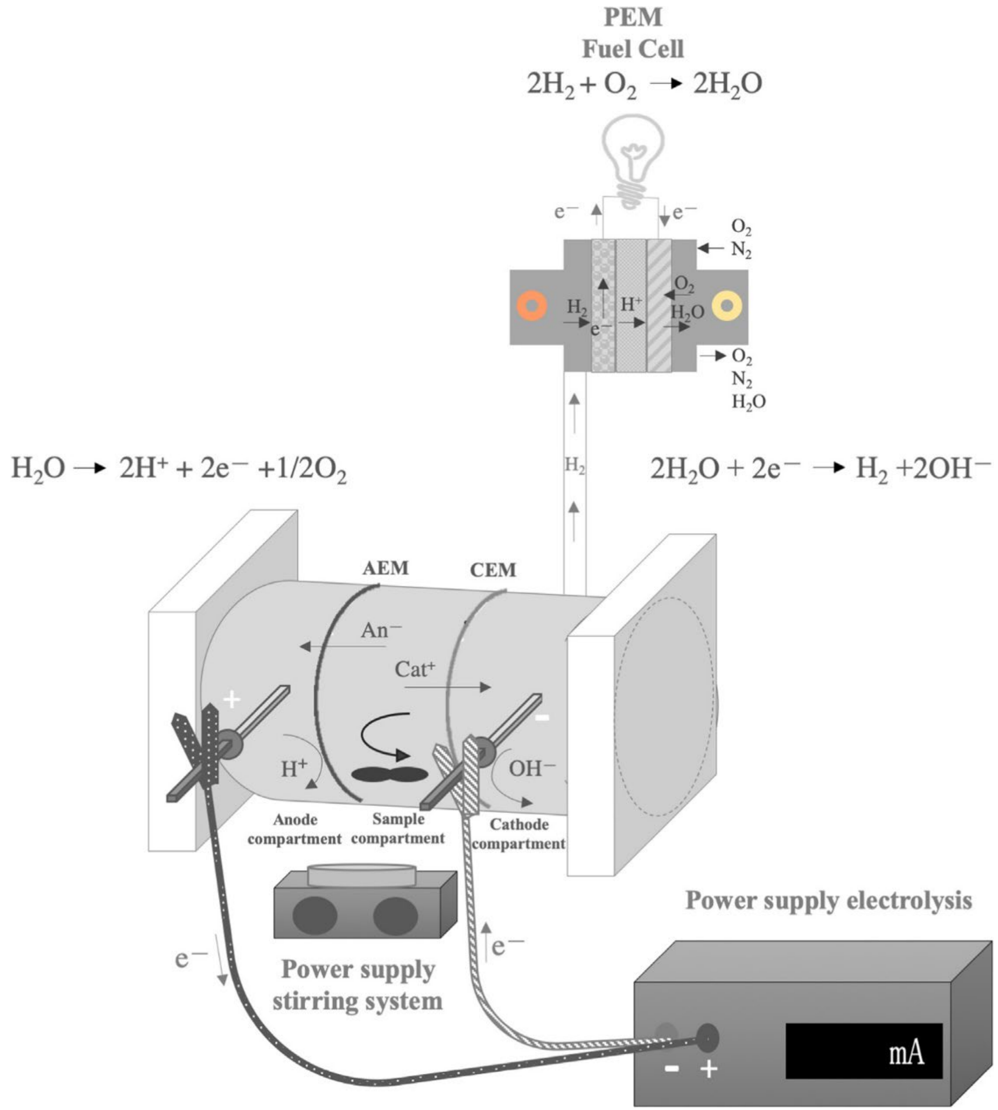


Fig. 1. Schematic of hydrogen production by a laboratory-scale ED reactor [106] with copyright permission from Elsevier 2019.

Table 3 Summary of metals, ions and salt recovery using ED.

Recovered metals/ ions/ salts/acid-base	Feed sources	ED techniques	Membranes used	References
Ag	Model solutions of $AgNO_3$ and wastewater from industrial plating plant	Experimental ED cell	Nafion-424, Ionac MA-3475, K-501, A-501	[109]
Al and acids	Foil industry waste acids	Diffusion Dialysis and Bipolar Membrane ED	AEM DF-120,	[110]
As	Actual geothermal water, NaCl, and NaOH solution	Laboratory scale 10-cell ED system	ACILYZER EX3B	[111]
As	Synthetic As_2O_3 solution	Tailor-made Ed stack	Cationic (SKS-C) and anionic (SKS-A) membranes	[112]
B and Li	Synthetic solution of $Li_2B_4O_7.5H_2O$	Lab scale PC-Cell ED 640 04	AEM-PC SK, CEM-PC SA, Bipolar Membrane-PC Bip	[113]
$CaSO_4$ and NaCl	Concentrated raw seawater	Dual-purpose ED and ED reversal	ACS, CMS, CMV, AMV	[114]
Ca and SO_2	Seawater and flue gas	Bipolar membrane ED	Bipolar Membrane	[115]
Ca and Mg	Seawater desalination reverse osmosis brines	Pilot scale ED and nanofiltration	NF270	[116]
Cd	Cd and Cyanide containing simulated electroplating wastewater	Laboratory scale five-compartment ED cell	NAFION 450, SELEMION AMV	[117]
Cd	Wastewater sludge from treatment plant	Laboratory-scale ED compartments	AEM-204 SZRA B02249C, CEM-CR67HUYN12116B	[118]
Cd, Cu, Pb and Zn	Synthetic solutions of Pb, Cu, Zn and Cd	Combined Ion exchange membranes and ED membranes	Strong ion exchangers, CMX and AMX produced by Tokuyama Co	[119]

Cd and Cyanide	Synthetic galvanic industry wastewater	Lab-scale ED	Nafion 450 and Selemion AMV	[120]
Cs	Prepared solution of CsCl salt	Hybrid ED-ion exchange membrane	CMI-7000	[121]
Cr	Anaerobic bioreactor effluent containing $K_2Cr_2O_7$	Laboratory scale ED	PC-SA type, PC-SK type, PC-SC type	[122]
Cu	Mixed $CuSO_4$ and H_2SO_4 solution	Lab scale hybrid ion exchange ED	Nafion 117	[123]
Cu	Model solution of $CuCl_2$ and HCl and rinse water	Recirculating ED system	IonacMA3475 Nafion423	[124]
Cu	Discharge of semiconductor manufacturer	Combined ultrafiltration and ED	SKS-A, SKS-C	[125]
Cu and Water	Synthetic Cu-containing wastewater mimicking electroplating wastewater	Laboratory scale combined ED and electrolysis process	-	[126]
Cu, Fe, and water	Synthetic and industrial wastewater	Lab-scale ED	Ionac MC3470 (cation) and MA3475 (anion)	[127]
Fe	Laboratory prepared H_2SO_4, HNO_3, $FeSO_4.7H_2O$ solution	Laboratory ED cell	CMX, AMX, Nafion 117, CMV	[128]
HCl	simulated chemosynthesis of aluminum foil wastewaters.	Integrated diffusion dialysis (DD) and conventional ED	AEM DF120	[129]
HCl and NaOH	Seawater desalination reverse osmosis brine	Pilot scale monopolar and bipolar ED	Neosepta CIMS and Neosepta ACS	[130]
K_2SO_4	Synthesized solution	Integrated ED metathesis-reverse osmosis-evaporation	Seleminon, Neosptep, lonsep, Ralex	[131]
Li	Synthetic solution of Li_2SO_4, $CuSO_4.7H_2O$, $MnSO_4.H_2O$ representative of Li-ion battery effluent	SED	Neosepta AMX and Neosepta AEM	[132]
Li	Li-ion solution contaminated with Na	SED	Lithium selective CEM	[133]
Li	Solution of LiOH, NaOH, KOH	ED	Thin plate of $Li_{0.29}La_{0.57}TiO_3$	[42]

Li	Synthesized Mg doped $LiMn_2O_4$	SED	Sulfonated poly composite CEM	[134]
Li	High Mg/Li ratio evaporated brine from salt lake	Single-stage and multi-stage SED	Selemion CSO and ASV	[135]
NaCl	Brine from seawater desalination plant	Integration of ED with nanofiltration	DL2540, homogeneous ion-exchange membrane	[136]
NaOH	Industrial wastes	ED	Cross-linked polysulfone based AEM	[137]
Ni	Synthetic nickel-plating rinse water using $NiSO_4$, $NiCl_2$, H_3BO_3	Bench-scale ED and industrial scale ED	Ionac MC-3470, Ionac MA-3475	[138]
Ni and Water	Synthetic electroplating effluent	Laboratory scale ED	Cationic ionac MC-3470, anionic (Ionac MA-3475)	[139]
Pb	Analytical grade $Pb(NO_3)_2$ salt and deionized water solution	Laboratory-scale ED cells	AR204SXR412, CR67 and MK111	[140]
Pb	Synthetic $Pb(NO_3)_2$	Commercial laboratory ED unit to simulate industrial ED conditions	Ralex CM-PES, Ralex AM-PES	[141]
Pb	$Pb(NO_3)_2$ solution	Combination of ED and adsorption	CEM(YLM001), AEM(YLM201),	[142]
SO_4^{2-}	Spent sulphuric acid from zinc hydrometallurgy industry	Laboratory and pilot-scale ED	Neosepta CMS, Morgane CRA, Selemion CHV, Nafion 117, Morgane ARA 17-10 AEM	[143]

In a cumulative sense, harnessing the recovered resources from ED presents a promising pathway toward achieving a CRE. Ongoing research endeavors and emerging opportunities continuously enhance the efficiency and possibilities of resource recovery. Among various sectors, the WIN holds immense potential for resource recovery. Through ED, the recovered resources not only reduce waste but also generate economic value while ensuring efficient resource utilization. Implementing ED and adopting resource recovery practices in the water sector enables a shift from a wasteful linear approach to a more efficient circular model.

2.4. Desalination of seawater and wastewater for a closed-loop economy

Enhancing resource productivity and protecting the environment have become focal points in the economic blueprints of numerous countries' governments. To achieve resource efficiency, governments have been implementing policies, regulations, and laws. As a result, the WIN is transitioning from a conventional end-of-pipe approach to a circular approach [144]. However, the economic aspect of wastewater circularity has not received sufficient attention. Furthermore, there is a need to establish connections between desalination in the WIN, specifically through ED, and the concept of a CRE. This will help address the research gaps associated with resource recovery.

Recent technological advancements in the water sector have prompted academics and governments to develop more efficient models for water management. Proposals have been put forward suggesting that CRE could serve as an effective framework for introducing sustainability in water management. The principles of a circular loop supply chain, waste minimization, value retention, and resource recovery are well-compatible with the water sectors. The sixth goal of sustainable development goals (SDG 6) states “clean water and sanitation”. As the water sector is subject to the industrial sector, SDG 9 “industry, innovation and infrastructure” and SDG 12 “responsible consumption and production” are also directly interlinked with the application of CRE in the WIN. While the other SDGs are also indirectly interlinked [145].

Water possesses unique characteristics and can exist in various physical states. One intriguing aspect is that water can be mixed with different types of chemical elements. It traverses human and natural systems, accumulating chemical elements along the way. However, water itself remains crucial to these systems and often requires purification to be in its pure form. This is where water purification becomes significant. As water is a polar substance that remains liquid at normal temperatures, the chemical substances mixed with water are typically salt-like compounds. A considerable portion of Earth's water is saline, emphasizing the importance of water desalination to render it suitable for specific purposes.

The CRE framework emphasizes the 6Rs: reduce, reuse, recycle, reclaim, recovery, and restore. Implementing these concepts in the WIN can facilitate the transition towards a circular closed-loop economy. ED as a viable option for water desalination, holds the potential to support the adoption of the circular economy in the water industry. This perspective is supported by various desalination plants, projects, and studies utilizing ED. Table 4 provides a summary of recent studies on water desalination by ED technologies.

Table 4 Recent studies in the literature of water desalination and recovered resources by ED.

Feed sources	Separated resources	References
Reject brine or saline wastewater	NaCl stream and desalinated water	[146]
Rejected brine	NaCl and desalinated water	[147]
Seawater	Desalinated water	[148]
Saline groundwater	Desalinated water	[149]
Natural seawater	Desalinated water, Mg, Ca	[150]
High-salinity wastewater	Water, Ca, Mg	[151]
Seawater	Water and NaCl	[152]
Brackish water	Water and NaCl	[153]
Sea water and brackish polymer flooding produced water	Desalinated water	[154]
Highly saline seawater	Desalinated water	[155]
Industrial saline effluent stream	Water, NaCl, HCl, NaOH	[156]
Spent water from kraft pulp mills	Desalinated water	[157]
Oil sands process-affected water and basal depressurization water	Desalinated water	[158]
Concentrated brine	Freshwater and hydroponic fertilizer solution	[159]

It was demonstrated that water desalination using ED is a viable method to reclaim the water (Table 4). This process proves highly efficient in reusing water repeatedly, resulting in cost reduction, decreased resource consumption, and mitigated environmental impacts associated with untreated wastewater discharge. Moreover, the reclaimed water from water desalination plants can be utilized for various industrial or domestic purposes. The desalination process not only recovers water but also restores its chemical and physical characteristics, facilitating the establishment of a closed-loop water resource system. Additionally, valuable resources accumulated in the concentrated brine during water desalination can be further reused and recycled to generate value-added products.

The potential of electrodialysis desalination as a key technology for achieving a CRE in WIN. The central theme of the figure revolves around the fact that, a closed-loop system can be established in WIN based on ED, highlighting the interconnectedness of various components and processes related to WIN. The figure showcases a comprehensive water management system, starting with the generation of wastewater on the left-hand side. The arrows signify the flow of water through different stages, emphasizing the concept of circularity. The treated wastewater undergoes electrodialysis desalination, represented by an electrodialysis stack, leading to the production of desalinated water. The desalinated water serves as a valuable resource for water industries, as indicated by the arrows branching out to different sectors such as industrial processes, agriculture, municipalities etc. This demonstrates the potential for water recovery and reuse, contributing to a more sustainable water management approach. Additionally, the figure highlights the valorization of by-products through resource recovery.

The concentrated brine, a residual stream from the desalination process, undergoes selective electrodialysis and reverse electrodialysis. These processes enable the extraction of valuable compounds and facilitate energy generation, respectively. The arrows depicting the conversion of the brine to value-added products and hydrogen fuel symbolize the utilization of these recovered resources, further enhancing the circular economy aspect. The figure succinctly encapsulates the central message of the paper, emphasizing the role of electrodialysis desalination in enabling water recovery, resource efficiency, and the generation of value-added products. It presents a visual representation of the interconnectedness between wastewater treatment, desalination, resource recovery, and circular economy in water industries.

2.5 Conversion of waste into value-added products by electrodialysis.

Desalination plants and other water industries generate substantial amounts of waste materials as by-products of their operations. However, these waste materials can be transformed into valuable products through appropriate processes and treatments. By finding alternative uses for these waste products, their inherent value can be realized. The approach of converting recovered materials into value-added products not only provides an economic advantage but also seeks the opportunity to reduce waste, contribute to economic growth, protect the environment and reduce pressure on resources. In the past, numerous studies have suggested the utilization of recovered resources from wastewater treatment plants using ED. However, for any reclaimed materials to be considered value-added products, they must serve a purpose and have a practical application. Table 5 illustrates the potential applications of value-added products derived from recovered materials using the ED process.

Table 5 Extracted value-added products using ED technology.

Recovered materials	Value added products	Alternative uses of products	Reference
Reject brines + CO_2	Carbonate salts, NH_4Cl and$NaHCO_3$	Pharmaceuticals, fertilizer industry, and glassmaking industry	[146]
Concentrated waste solution	Hydroponic fertilizer containing Mg^{2+}, Ca^{2+} and SO_4^{2-}	Plant nutrients	[159]
Seawater desalination brine	NaOH and HCl	Pulp and paper, batteries, soaps, and chemicals	[130]
High salinity water and dissolved CO_2	Desalinated water, inorganic acids and carbonate salts	Chemical industry, paints, and dyes industries	[160]
Waste acids from electroplating and acid pickling	Organic acids, formic acids, acetic acids, and malonic acids	Food preservative and pharmaceuticals	[161]
KCl from mineral extraction industries	KNO_3	Fertilizer	[162]
Sodium L-ascorbate from food industries	Vitamin C	Essential for human	[163]
Sodium Naphtenates from petroleum industries	Naphthenic acids	Oil soluble metal soaps, wood preservation, tire, and adhesion promoters.	[164]
$ZnCl_2$ from zinc hydrometallurgy	$ZnSO_4$	Leather preservative, dietary supplements	[165]
Penicillin G extracted from aqueous buffer solution	Ampicillin	Medicine	[166]
Chemical effluents	Organic acids	Food additive and pharmaceutical industries	[167]
Recovered by-products from beverage industry	L-malic acid	Foods and cosmetics	[168]
Recovered concentrate	Acid (H_2SO_4)	Fertilizer, pigment and dyes	[169]
SW concentrate	Salts	Food preservation and flavoring	[114]
SW desalination brine	Phosphate NaOH and HCl	Water treatment chemicals	[116]
Recovered grass silage juice	Lactic acid and amino acid	Preservative, curing agent, flavoring agent and pharmaceuticals	[170]
Brine from desalination industry	NaOH and HCl	Pulp and paper, batteries,soaps and chemicals	[130]
Recovered by-products from fuel industry	Biodiesel	Transportation and energy generation	[171]
Brine from desalination plant	Salts and low salinity water	Industrial use, flavoring andcuring	[172]
Concentrate from RO	NaOH and HCl	Pulp and paper, batteries and chemicals	[173]
Recovered anaerobic swine digestate	Nitrogen, ammonium, potassium, chloride, phosphate, and water	Bio-nutrient, chemicals and fertilizers	[174]

Reverse osmosis discharged brine	$NaCl$	Food preservation, and flavoring	[175]
Recovered anaerobic digestate from food waste treatment	K^+, NH^{4+}, Cl^-, nitrogen and phosphorus	Nutrients, chemicals, and fertilizer	[176]
Digested sludge concentrate from wastewater treatment	NH_4^+	Fertilizer industry and chemical industry	[177]
Digestive slurry	PO_4^{3-}, SO_4^{2-}, NH^{4+}, K^+, Ca^{2+} and Mg^{2+}	Nutrients and chemical industry	[178]
Concentrate from water desalination plant	$MgCl_2$	Mineral supplement	[179]
Recovered wastewater from Aluminum finishing industry	H_2SO_4	Battery, dye, and glue manufacture	[180]

Table 5 provides a comprehensive overview of potential applications for the produced value-added products from ED. This table serves as a valuable reference, showcasing the diverse range of possibilities that arise from the conversion of waste through this innovative technology. It is important to be circumspect about implementing waste conversion by considering factors like process optimization, scalability, and cost-effectiveness, which is still under study of numerous prospects. Indeed, waste conversion is a promising avenue for the achievement of CRE.

2.6 Latest case studies of EDDRR from WIN for a CRE.

Several case studies pertaining to the practical implementation of resource recovery through Electrodialysis (ED) were undertaken and analyzed (Table 6). In these case studies, a comprehensive analysis of Electrodialysis Reversal and Recycling (EDDRR) projects was conducted. The studies scrutinized the attributes of the feed sources, including the composition of feed materials and the potential for recovering materials (as detailed in Table 6). Furthermore, these investigations assessed the energy requirements and the concentration levels of the recovery materials. It is noteworthy that these case studies encompassed a range of accessibility levels, spanning from pilot-scale resource recovery projects to laboratory-scale examinations.

The large-scale practical implementation of ED technologies for resource recovery dates back to the 1970s. An early example can be found on Takami Island, Japan, where ED was employed to recover salt and freshwater from seawater, achieving a daily recovery rate exceeding 10 tons of materials [181]. Substantial advancements in the practical implementation of ED for resource recovery were observed in the 1980s, particularly in countries like India and Japan, where treated water was recovered from saline and brackish water sources, with recovery rates ranging from 1 to 10 tons per day [181-182]. In the 1990s and 2000s, significant success was achieved in the large-scale desalination and water treatment plants for water recovery, particularly from brackish water or surface water sources, in countries such as Spain, Algeria, Bahrain, and Japan [181-186].

Table 6 Case studies of EDDRR in WIN for a CRE.

Studied ED cases	Feed Sources	Recovered materials	Energy required	Quantity of the recovered resources	Year	References
ED for recovery of Ni, P and N	Electroless nickel-plating (ENP) wastewater	Ni^{2+}, NH^{4+}, total phosphorus (TP) and NO^{3-}	20 mA/cm^2	-	2023	[187]
Metal ions (Cu) recovery via ED	Concentrated plating wastewater	Cu as CuO and Cu_2O	3.5–5.3 kWh/ Kg-Cu	93%–96% Cu-selective recovery	2022	[188]
University of Naples Federico, Italy	-	Freshwater	5-45kWh/ m^3	230-920 m^3/d	2020	[189]
ED for the recovery of lithium	Primary and Secondary lithium sources	LiCl, LiOH and Li_2CO_3	-	Efficiency, 80%	2019	[190]
Recovery of citric acid using ED	Fermented liquid	Citric acid ($C_6H_8O_7$)	-	Highest acid recovery of 97.1%	2017	[191]
Universidad de Antofagasta	Brackish water	Freshwater	2.16kWh/ m^3	-	2017	[192]
ED for processing waste solutions	Sodium Sulphate waste salts	NaOH and H_2SO_4 solutions	7.5 A/dm^2	NaOH= 75.9%, and H_2SO_4 =49.8%	2016	[190]
Chelluru, South India	Brackish water (3600 ppm TDS)	Freshwater	2.47 kWh/ m^3	6-15 m^3/d	2015	[193,194]
The Depurbaix Wastewater Treatment Plant (WWTP)	Municipal wastewater	Treats wastewater for agricultural use	-	More than 57,000 m^3/d	2010	[183]
Zaragoza, Spain	Brackish water (3000-5000 ppm TDS)	Freshwater	1 kWh/ m^3	4.32 m^3/d	2010	[195]
The Abrera Drinking Water Treatment Plant (DWTP)	Raw water directly from the Llobregat River	Drinking water	0.6 kWh/m^3	3 m^3/s to 4m^3/s	2009	[183]
In desert of Hass khebbi, Algeria	Brackish water (3500 ppm TDS)	Freshwater	8981 kWh/year	7890 m^3/year	2009	[185]
University of Alincante, Spain Wastewater treatment project	Brackish water (2300-5100 ppm TDS)	Freshwater	0.7-1.7 kWh/ m^3	1.32 m^3/d	2006	[184]

University of Bahrain, wastewater treatment project	Brackish water (1000-5000 ppm TDS)	Treated water	-	1.14 m^3/d	2002	[182, 196]
Fuke City ED Plant in Japan	Brackish water (700 ppm TDS)	Treated water	0.6-1 kWh/ m^3	200 m^3/d	1990	[181-182]
Desalination plant in Rajasthan, India	Brackish water (5000 ppm TDS)	Treated water	1 kWh/kg of salt removed	1 m^3/d	1986	[182]
Treatment plant on Oshima Island (Nagasaki), Japan	Seawater	Quality water	25 kW/m^3	10 m^3/d	1986	[182]
Thar Desert, India	Brackish water	Freshwater	1 kWh/kg of salt removed	1 m^3/d	1986	[181]
Takami Island, Japan	Seawater	Salt and Freshwater	-	10 m^3/d	1977	[181]
Desalination plant in Spencer Valley, New Mexico (USA)	Water of about 1000 ppm TDS	Treated water	0.82 kWh/m^3	2.8m^3/d		[182]

Critical advancements in recent years have been even more noteworthy, with lower energy requirements compared to earlier cases and improved recovery rates. Furthermore, the scope of resource recovery from wastewater and residual streams has expanded and diversified, including the recovery of metals like lithium, nickel, and copper from various feed sources [187-194]. The large-scale practical implementation of ED technologies for resource recovery dates back to the 1970s. An early example can be found on Takami Island, Japan, where ED was employed to recover salt and freshwater from seawater, achieving a daily recovery rate exceeding 10 tons of materials [181].

Substantial advancements in the practical implementation of ED for resource recovery were observed in the 1980s, particularly in countries like India and Japan, where treated water was recovered from saline and brackish water sources, with recovery rates ranging from 1 to 10 tons per day [181-182]. In the 1990s and 2000s, significant success was achieved in the large-scale desalination and water treatment plants for water recovery, particularly from brackish water or surface water sources, in countries such as Spain, Algeria, Bahrain, and Japan [181-186]. Critical advancements in recent years have been even more noteworthy, with lower energy requirements compared to earlier cases and improved recovery rates. Furthermore, the scope of resource recovery from wastewater and residual streams has expanded and diversified, including the recovery of metals like lithium, nickel, and copper from various feed sources 187-194].

Recent studies have made substantial strides in enhancing our comprehension of the practical implementation of ED) technology for freshwater production, desalination, and resources recovery within the framework of CRE practices. Ongoing research endeavors are primarily focused on several key areas, including cost reduction, process optimization, scaling efficiency, improved recovery rates, and the minimization of the carbon footprint associated with ED operations. These collective efforts aim to advance the application of ED technology, rendering it more economically viable, operationally efficient, and environmentally sustainable.

2.7. Reduction of waste and energy usage through electrodialysis in water treatment

Currently, our world is facing a critical situation characterized by rapid environmental degradation and an impending energy shortage. In response to this crisis, academics, organizations, governments, and inter-governmental panels are actively seeking innovative solutions. Every facet of our lives is recognizing the need to embrace cleaner production practices.

Cleaner production entails the reduction of waste and the efficient utilization of resources. It represents a proactive strategy aimed at enhancing efficiency while deriving benefits from environmental resources [196]. By adopting cleaner production practices, we can minimize our ecological footprint and promote sustainable development Water treatment processes typically produce clean water as their primary output. However, in desalination plants, for every liter of potable water produced, approximately 1.5 liters of reject brine is generated [196]. Unfortunately, this reject brine is often disposed of directly into the sea, representing an end-of-pipe approach.

This practice has significant negative impacts on the environment and poses harm to aquatic species, and also this action has immense adverse effects on the environment and is harmful to aquatic species. Additionally, the highly concentrated brine mixed with other chemicals can bring about long-lasting effects on coastal areas and contribute to pollution. Other than the direct discharge of reject brine into the sea, disposal of reject brine may include methods like deep well injection, land disposal, and evaporation ponds [146]. The rejected brine contains valuable components like Na, C, Mg, and Ca, to name but a few. These components can be used to react with CO_2, which is already a proven and applied technology to capture and sequestrate carbon to combat the carbon emission problem of the present world. This process converts the waste of water treatment industries into value-added products like $NaHCO_3$ and NH_4Cl [146].

Among the various established methods of water treatment and desalination, ED has proven to be the most viable option in terms of both output water quality and energy usage. Greiter et al. [197] conducted a comparative study between ED and ion exchange, focusing on the total energy demand. The study concluded that ED exhibited a cumulative energy demand of 97 and 91.7 Wh/mol, while ion exchange had cumulative energy demands of 291.1 and 190.5 Wh/mol. These findings clearly establish ED as the more energy-efficient choice. Considering both cost and energy usage, ED emerges as an effective method for water treatment. The combination of energy efficiency, economic viability, and high-quality output positions ED as a highly efficient approach. By utilizing ED, water treatment processes can achieve optimal results while minimizing energy consumption and operational costs. The superior performance of ED in terms of energy efficiency underscores its importance in sustainable water treatment practices. Its advantages make it an attractive option for industries and communities seeking efficient and cost-effective solutions for water purification and desalination.

By highlighting the crucial role of desalination in adopting a sustainable approach within WIN, showcasing the potential for converting waste materials into value-added products through ED, and emphasizing the benefits of waste reduction and energy efficiency, this review presented a comprehensive overview of how ED can contribute to establishing a CRE in WIN. The integration of ED in desalination plants not only addresses sustainability concerns but also presents a novel opportunity to establish a CRE within WIN. The implementation of ED in desalination plants could contribute to enhancing water supply resilience in water-scarce areas while simultaneously reducing dependency on limited freshwater sources.

3. Techno-economics and environmental sustainability of EDDRR from WIN for a CRE.

The sustainability of ED desalination is evaluated based on economic, technical, environmental and social factors. Integrating renewable energies (RE) with ED desalination improves water sustainability, making RE a practical solution to address water scarcity [198-199]. This section comprehensively analyzes the techno-economic aspects and environmental impact of ED as a treatment process that aims to contribute to the environmental management of desalination and resource recovery for a CRE.

3.1. Economic factors

3.1.1. Cost Sources of ED

The total expense of ED includes fixed charges for depreciating the plant investment and operational costs, which cover the cost of electricity and regular maintenance [200]. The investment costs cover depreciable and non-depreciable goods, including electrical devices, membranes, motors, ED stacks, and surveillance and control systems [201]. The operating costs of an ED comprise electricity, labor, membrane replacement, chemicals, insurance, and fixed costs. The fixed fees may be determined by utilizing a capital cost amortization approach that can be split into direct and indirect expenses [202].

Direct prices include expenditures for land, infrastructure, machinery, well drilling, salt removal, and membranes. Like direct costs, indirect costs include shipping costs, legal and advisory fees, unforeseen expenses, and building overhead costs [202]. As a result, the annual operations costs are used to calculate the product cost, as indicated in the detailed cost sources in Fig. 2. Design factors for ED, including feed flow salinity, linear flow rate, recovery proportion, cell size, and buffer darkness effect, among others, have a considerable impact on the power cost and fixed cost [203]. As a result, the current density affects the overall costs of the product and will be at its lowest point at a particular current density.

These costs include energy expenditures, amortization, and maintenance. This relationship is visually represented in Fig. 3A. In order to demonstrate the impact of different cost elements, several studies [204-206] were conducted to analyze the feed salinity of ED. The findings revealed that when considering all cost components, power, fixed, and other charges accounted for 28.65%, 24.89%, and 46.46% of the unit product water costs in ED plants, respectively. However, when excluding the pre-and post-treatment processes, the cost breakdown for ED water production showed that power, fixed, and other charges contributed 43.52%, 19.70%, and 36.78% of the total cost, respectively. Fig. 3B illustrates the connection between expenses and feed concentration. This figure provides a schematic representation of the functioning costs and how the feed water concentration affects the overall desalination expenses.

3.1.2. Product water cost

When choosing a desalination technique depending on the salinity of the water supply, it is essential to compare the price of product water at various feed concentrations to make informed decisions. The desired product water salinity is set at 0.2 ppt, which is considered excellent according to the World Health Organization (WHO) [207]. The feed salinity for ED is varied from 0 to 50 ppt. Zhang et al. [208] conducted a study on the cost of product water using ED, keeping the product concentration fixed at 0.2 ppt. The price of product water for ED is 0.499 $\$/m^3$ at a salinity of 8 ppt. This implies that groundwater and other low-salinity sources are suggested for desalination via ED. ED is not a practical solution for high salinity levels (> 9 ppt, close to seawater salinity). For instance, when dealing with 5 ppt of water salinity (representing saline water), ED produces a product water cost of 0.384 $\$/m^3$. According to Zhang et al., [208] the product water cost for ED increases to 1.532 $\$/m^3$ as the feed salinity rises to 35 ppt (representing saltwater).

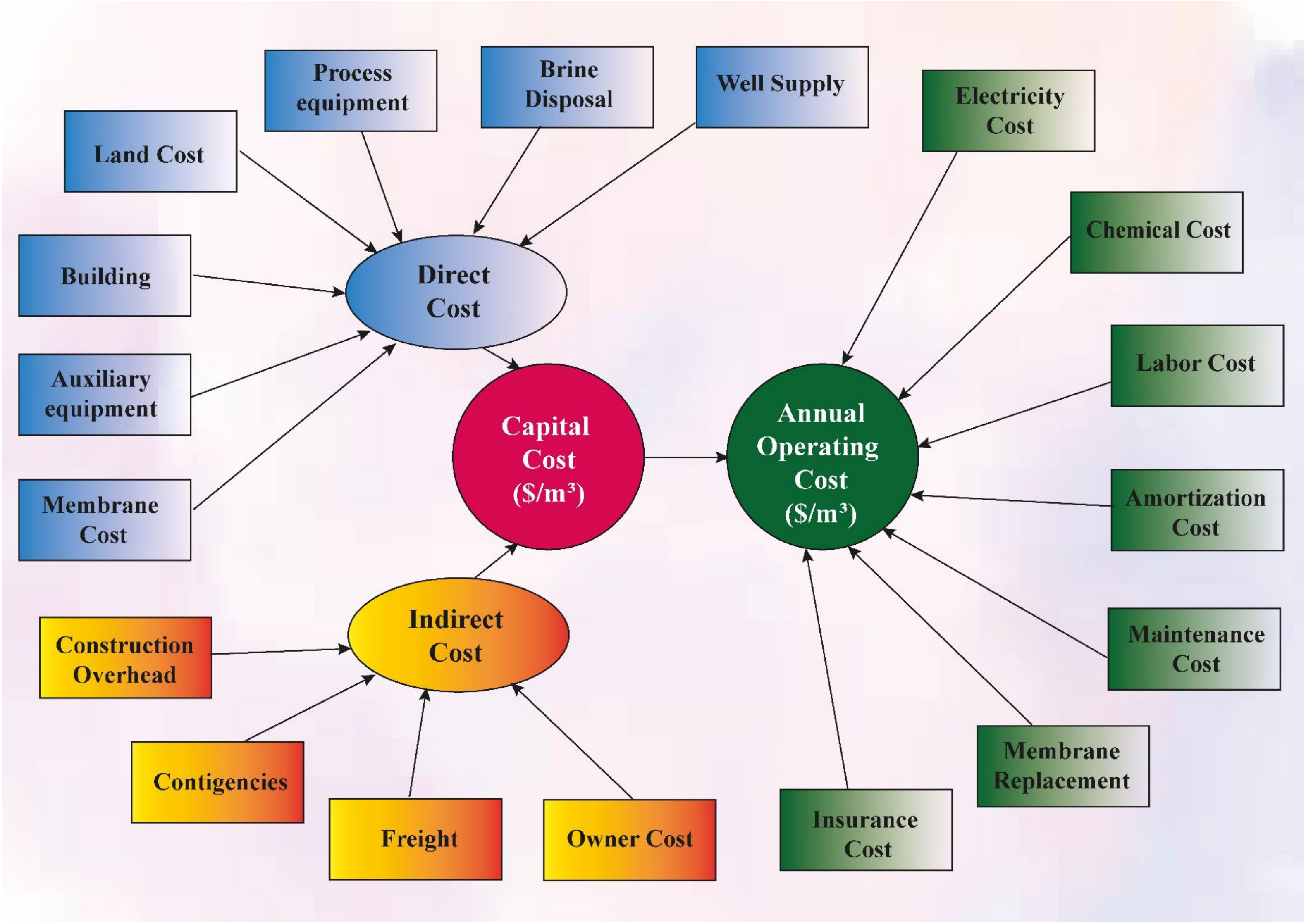


Fig. 2. Economic model conceptualization for EDDRR in WIN for a CRE.

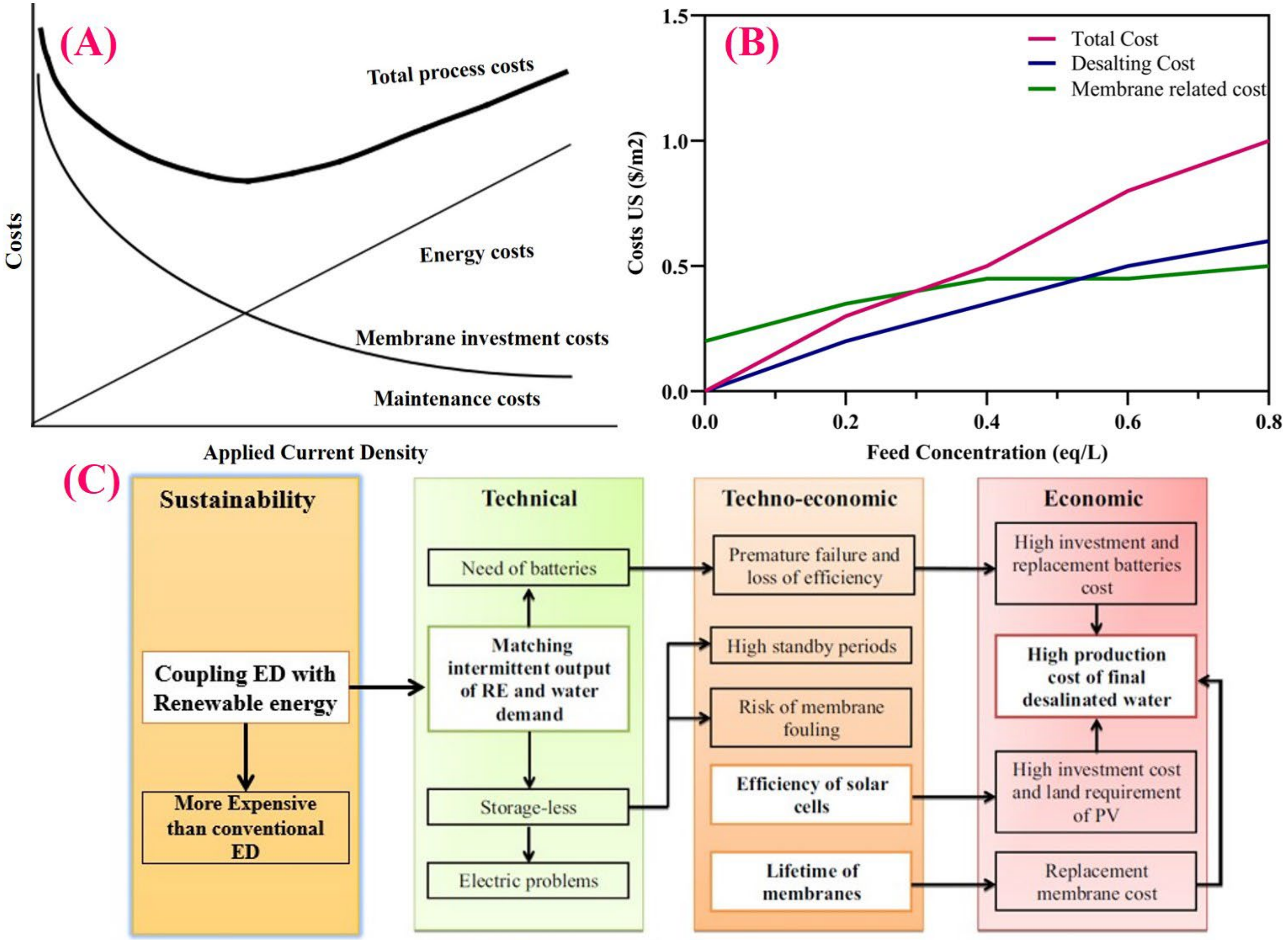


Fig. 3. Schematic diagram represents the relationship between (A) process costs and the current density, (B) the process costs and the feed concentration (C) ED with RE [205] with copyright permission from Elsevier 2020.

3.2. Environmental factors

3.2.1. Greenhouse gas (GHG) emission

The environmental impact of particular ED techniques is assessed using the DROC decarbonized RO concentrate (DROC) and decarbonized ED concentrate DEDC), focusing on the primary sources of CO_2 emissions at the current WWTP). Table 7 compares the CO_2/m^3 of water produced by various ED system components. It reveals that the CO_2 emissions from the WWTP are approximately twice as high as those from electricity consumption. Similar results for the UF + RO process emissions may be found at the Torreele plant and the ED pilot, measuring 0.26 and 0.30 kg CO_2/m^3, respectively. However, when factoring in the decarbonization step, these values increase to 0.94 and 0.57 for the DROC and DEDC methods [209-211]. This underscores the importance of considering ED technologies, as their environmental impact in terms of CO_2/m^3 of water can be significantly lower when renewable energy is used as the power source compared to conventional treatment methods.

Table 7 CO_2 emission/m^3 water generated from various units of ED process (current density 50 A/m^2 and flow rate 12 L/h per cell) [207].

CO_2 Emission	WWTP	Torreele	ED	ED + DROC	ED + DEDC
Energy Consumption (kWh m^3 effluent)	0.2	0.77	0.9	0.96	0.91
Electricity (kg CO_2 m^3 effluent)	0.07	0.26	0.3	0.32	0.31
Operational Process (kg CO_2 m^3 effluent)	0.14	N/A	0	0.62	0.26
Total CO_2 emission (kg CO_2 m^3 effluent)	**0.21**	**0.26**	**0.3**	**0.94**	**0.57**

3.2.2. Other possible environmental impact issues

3.2.2.1. Emission of O_2 and H_2 gases

Besides CO_2 emissions, the ED system may give rise to additional emission and discharge concerns. Specifically, the ED stack continuously generates O_2 and H_2 during operation. While O_2 poses no environmental issues, H_2 poses a safety risk to the system and the operational staff due to its potential for detonation. Generous et al. [207] investigated that the stack produces approximately 12 mol H_2 (eq. around 0.27 m^3 of H_2 gas)/m^3 of ED product. Currently, no practical method is available to collect and use the O_2 and H_2 produced by the ED process [7].

3.2.2.2. Organic compounds (OCs) discharge

According to earlier research, only 10% of the organic portion [212-214] is present in the ED concentrate. The remaining OCs are either more extensive or free of charge in the ED dilute effluent. Ozonation can peroxidize these compounds post-treatment, transforming them into degradable forms. It is feasible to return the ED dilute to the biological remediation unit to further diminish persistent organic pollutants (POPs) by applying ozonation to the ED dilute. Therefore, it is anticipated that the organic molecules in the ED concentrate will have a lesser environmental impact than those in the RO concentrate.

3.2.2.3. Salt discharge

The salinity level of the entire ED process was found to be 25 mS/cm, which is diluted with the ultra-filtration (UF) concentrate [215]. However, the canal, a surface water supply, may experience negative consequences due to the excessive salinity brought on by the combination of UF and ED concentrates. Direct discharge into the sea, which has a conductivity of 40–50 mS/cm, is a possible substitute if dumping the ED focus into the canal is forbidden owing to environmental concerns [216]. The release of the ED concentrate into the sea is projected to have no substantial net impact due to the relative amounts of seawater, and ED concentrate [206].

3.3. Social factors

Enhancing social acceptance of ED plants can be achieved by creating job opportunities [217]. The construction of new facilities still requires local employment [218]; for instance, no matter the technology used, it is projected that a facility with a capacity of 189,000 m^3/day and a 25 km pipeline will require around 280 temporary employees (80 for the plant and 200 for the pipes) [219].

In terms of ED operation, a desalination facility typically employs workers across management, administration, operation, maintenance, and training-safety-lab [220]. Two full-time employees are required for ED technology with a 3 MGD (11,364 m^3/day) capability, assuming 8 hours per day and 176 hours per month [219]. These employment figures demonstrate a wide range of intensity, ranging from $1.03\times10^{-4}\times10^{-3}$ m^3/ day permanent positions. This variability in employment intensity can be attributed to the limited availability of data in the area and the fluctuating capacity of ED plant. It is important to consider that changes in the scale of an ED plant will impact the required workforce.

3.4. Technological factors

Technical challenges play a significant role in limiting the performance of the ED system and must be addressed to unlock its full potential. Finding the best fit between the fluctuating output of renewable energy (RE) and water demand (WD) is one of the most critical technical challenges when incorporating ED with RE [219]. Demand-side management and power management, which involve hybrid energy units capable of delivering a continuous energy output and only functioning when appropriate energy is available for desalination, respectively, have been put forth as two viable strategic solutions [218].

Demand-side management faces the challenge of establishing efficient energy storage systems to smooth out the fluctuating output of RE [221]. However, high ambient temperatures, battery aging, and improper operating conditions can lower the efficiency due to self-discharge [15,222]. In contrast, the main obstacle to power management is the high cost of producing desalinated water compared to conventional energy sources. However, ED tolerates variations in inlet energy and may be quickly started and stopped, making it appropriate for intermittent operation [213]. Furthermore, ED performs well when subjected to fluctuating fluxes from RE, showcasing its ability to handle periodic energy inputs effectively.

3.5. SDG analysis and sustainable solution for the integration of ED with CRE

EDDRR for WI in CRE is a part of SDG No.7, which focuses on "affordable and clean energy" to ensure universal access to affordable, reliable, sustainable, and modern energy. Annually, the desalination process consumes more than 850 MT of oil to treat a daily volume exceeding 90 million m^3, producing 76 MTof CO_2. This amount is projected to increase to 218 MT of CO_2 by 2040 [220]. Cleaner production practices have been developed to promote CRE. These practices prioritize the integration of ED with RE.

ED technology has integrated solar, wind, and geothermal energies for desalinating and resource recovery (RR) [205]. In 2011, approximately 9% of the solar energy used worldwide for desalination was utilized for ED [223]. Combining ED with photovoltaic (PV) technology offers numerous advantages, including reducing environmental and economic challenges [208]. Technical difficulties are reduced by Fernandez-Gonzalez's analysis of the viability of PV-ED systems with no energy storage [219]. Numerous investigations have shown that PV-ED systems effectively sterilize seawater, especially in distant places. In 2018, Campione et al. [223] investigated the potential installation of PV-ED systems in Northern Chile due to its solar radiation of 7-7.5 kWh/m^2/day and rivers with salinity levels exceeding 4000 mg/L, making it an attractive option for solar-powered ED technology [15]. In Fukue City, Japan, a 65 kWh PV array was erected in 1990, creating the most extensive PV-ED system [205].

With an energy usage of 0.6–1 kWh/m^3, this system has a daily production capacity of 200 m^3. Shen et al. (2014) developed a PV-ED system for groundwater desalination that is energy-efficient and reasonably priced for community use [218]. In contrast to ED systems powered by fossil fuels, PV-ED systems for seawater save up to 0.724 kg CO_2-eq./m^3 [208]. Empirical research is being done to assess the viability of producing potable water by combining ED desalination with wind energy [224]. It has been determined that wind-powered ED is a straightforward, affordable, and effective alternative. Al-Amshawee et al. [172] investigated the desalination of brackish subsurface water with a sodium chloride concentration of 5000 mg/L using a wind-ED system. At 10 m/s of wind speed, this setup produced 4.15 kWh/m^3, whereas at 2 m/s, it produced 2.52 kWh/m^3 [205]. Another investigation discovered that underground desalination with wind-ED technologies might have made 2.02-3.62 m^3/m^2/day of water, exceeding the 0.2-2.3 m^3/m^2/day claimed capacity of PV-ED systems [207]. Table 8 summarizes the ED technologies with associated costs, resource recovery, outcomes, benefits, and drawbacks of the latest ED studies for EDDRR in WI for a CRE.

Desalination and RR are two processes that can benefit from integrating ED with operations supported by renewable energy (RE). However, due to the substantial consumption of energy of ED associated with high levels of salt and the relatively limited lifetime of membranes while running at high current densities, this integration has not been thoroughly explored [15, 213, 225]. Fig. 3C summarizes the performance review regarding combining ED with RE.

Table 8 Electrodialysis studies for desalination and resource recovery in the WIN for a CRE perspective.

ED Technologies	Resource recovery & associated cost	Outcomes and Consequences of the ED Process	Issues / Limitations	References
Power free electrodialysis (PFED) for fresh water production	- Water recovery 65%.	- technically viable, - economically beneficial, - battery-free; - to produce energy, the RED enzyme can be fed the ED concentrate;	- Concentration-based polarization; - decreased membrane perm selectivity at high doses; - In comparison to RED internal resistance, ED resistance is somewhat higher.	[226]
Desalination of brackish groundwater using monovalent and divalent membranes	**Pilot scale ED**: - Energy usage (1.3 kWh.k/gal); - Removal of Salt (0.42-0.74 kg salt/m^2 kW/h); - Recovery of water (55%).	- higher salt removal with increasing current density; - stable ion selectivity;	- Salt removal efficiency decreased as flow rate increased - In bench and pilot scale ED, the same desalting efficiency found as the regular grade membranes	[15]
Bench scale batch ED upgrading biorefinery streams	**Bench scale ED:** - Energy usage (1.9 kWh k/gal); - Removal of Salt (5.17- 4.97 kg salt/m kW/h); - Recovery of water (50%)	- the ED at a greater flow rate to produce more water - The outcomes of bench-scale testing can be used to forecast the ion selectivity of pilot and possibly full-scale ED.	- Electrostatic repulsion decreased the rate of divalent cation transport.	[59]
EDBPM-PV uses bipolar membranes to separate HCl and NaOH from seawater	- Efficiencies (69–104%); - Energy usage (0.44–1.59 kWh/kg); - Removal of Salt (96%).	- Increased ionic transfer rate when salt concentration was higher. - Cost-effective.	- Organic losses accounted to 0.3–6.3%	[223]
Utilizing ED, extract chemicals from a copper plating bath devoid of cyanide.	- Efficiency of PV (14.2%); - Energy usage (7.3 kWh/kg) - Removal of Salt (95.6–98.2%)	- PV significantly reduced the amount of energy required to produce one kilogram of HCl from 7.3 to 4.4 kWh; - ED method renewable energy speeds up desalination and uses less energy.	-	[58]
Utilizing ED, desalinate biorefinery effluents	- Removal of minerals (90%); - Resources extraction (> 80%).	- Restored the membrane's original characteristics - Recovered the water and inputs of chemicals and lowering waste production.	- Reverse diffusion; - organic acid mixed interconnected with membrane fixed groups.	[205]
Production of Alpha-ketoglutaric (AKG) acid via EDBPM	**Bach scale ED properties:** - Membrane area (0.0121 m^2) - Time period (3 h); - Max. voltage (30V).	- Cost-effective; - High permeability. - Impacts energy use and desalination level.	- The resistance of the stack was raised by organics crossing the membrane.	[227]
Electrodialysis with polysulfone-based membrane for H_3PO_4 purification	- Efficiency (71.8%); - Energy Usage (3.72 kW h/kg); - Average production of AKG (4.83 g/L).	- High AKG concentration, high current efficiency, and low energy consumption were the outcomes of ideal conditions.	- To industrialize EDBM, additional research is necessary.	[190]
Pilot scale ED for nutrient recovery	- Efficiency (68.13%); - Average cost of membrane ($50\ \$/m^2$); - Lifetime (3 year); - Energy usage (2.73 kw h/kg); - Electricity cost ($0.15\ \$$ kw/h).	- More than 60% of Fe, Mg, and Ca were eliminated	-	[228]
ED for inorganic acid recovery	- Efficiency (76%); - Energy Usage (4.9 kWh kg/N); - Total feed treated (5400 L)	- Economically promising technology for nutrient recovery is ED;	- The membrane boundary layer's ion concentrations decreasing; - NH_4-N total loss of 28%; - Dissociation of water	[229]

		- effective cleaning practices resulted in functional long-range viability		
Semi-industrial EDBPM for deacidification of Cranberry juice	- Effective membrane area (0.785 cm^2); - volume (about 50 mL).	- The simulation and empirical results agreed well.	- Leakage of acid.	[230]
ED ultrafiltration for Penicillin G and sulfate ions separation	**Batch mode:** - Total surface area (0.834 m^2); - Conductivity (2.2-2.3 mS/cm); - Time period (95 h); - Migration rates (61.23-38.13 mg/L.min).	- Green technologies; - Reusing the recovery solution boosts conductivity and results in a 42.9% reduction in energy consumption;	- After 3 hours of therapy, potassium began to escape through the anion-exchange membrane. - Leakage of H+ may have contributed to the plateau.	[231]
ED for HCOONa separation	- Effective membrane area (214.7 cm^2); - Minerals removal rates (69-84%); - Recovery rate of penicillin G. (10.7 $/kg)	- There was no noticeable fouling; - recovering 203 tons of penicillin G saved 203,000 m^3 of freshwater; and recovering 1000 tons of penicillin G year resulted in a profit of $6.85 million.	- Stack resistance; - Water splitting at the membrane surface alters pH.	[202]
Membrane scaling in the ED	- Efficiency (70%); - HCOONa purity rate (87%); - HCOONa recovery rate (69%); - Energy usage (96 kWh/m^3).	- No detectable pH change; - formic acid leaks and diffusion did not affect the current efficiency.	- The current efficiency is decreased by OH- leakage	[89]
Industrial brine treatment using reverse osmosis (RO) and EDR	- Flow rate (30 mL/min); - Time duration (5 h); - Current density (18 mA/cm^2).	- All membrane sides are devoid of precipitation; - An increased mass transfer due to greater electroconvection - The concentration profile is relaxed by a pulsed electric field.	- Low mass transfer as a result of the funnel effect.	[232]
Seawater and municipal wastewater treated with RED pilot plants	- Operation period (8 h); - Removal efficiency (7.1%); - Recovery of Water (85%); - RO brine reduction rate (6.5times); - Conductivity reduction (50%).	- Capable of producing highly concentrated brine; - Organic fouling was undetectable even after six days of nonstop operation.	- EDR resistance grew over the course of the 8-h process; - Ion depletion-related inflection points; - Using a current greater than the limiting current caused polarization; - CaCO3 precipitation occurred.	[233]
ED for removing Cr ions using magnetic CEM & cobalt ferrite nanoparticles	- Total membrane area (250 m^2); - Velocity (1.5 cm/s); - Energy efficiency (11.4- 13.3%); - Energy production (95.8 W).	- Sustainable energy source; - improved the water content, perms electivity, and ion exchange capacity of the membrane in addition to increasing its hydrophilicity and conductivity.	- Spacers being clogged; - Fouling from inorganic precipitation.	[234]

3.6. Scaling-up challenges of ED for resource recovery and desalination in WIN for a CRE

Electrodialysis (ED) is widely acknowledged as a valuable technology for resource recovery and desalination, offering sustainable solutions that alleviate the strain on natural resources. However, the application of electrodialysis is not without challenges and limitations, which can hinder its effectiveness in resource recovery and desalination processes. In the transition from smaller laboratory or pilot-scale operations to larger, extensive implementations, Electrodialysis (ED) technologies are accompanied by a set of challenges and limitations, which can be delineated as follows:

Membrane fouling (MF) poses a significant challenge, as it diminishes the lifespan of ion exchange membranes and compromises the efficiency of resource recovery. This phenomenon arises from the presence of organic and colloidal materials in the feed solution. MF manifests as an increase in electrical resistance and physical damage to the membrane, particularly when processing specific types of solutions. The challenges associated with membrane fouling (MF) can be effectively addressed through a range of strategies. These strategies encompass modifications to the surface properties of the membrane, including alterations to hydrophilicity, charge, and roughness, often achieved through the incorporation of modified components such as nanoparticles. Furthermore, pretreatment of the feed solution, as detailed in reference [235], utilizing methods such as chemical precipitation, coagulation, filtration, or other techniques designed to reduce the concentration of fouling agents [223], has proven to be effective. Another avenue for mitigating membrane fouling involves the adjustment of operational conditions, such as variations in feed solution concentration, pH levels, or flow rates. As proposed by Oztekin et al., various physical techniques, including forward flushing, backwashing, vibrations, and ultrasounds, have demonstrated efficacy in the removal of fouling agents from membranes [236].

The operation of an Electrodialysis (ED) stack necessitates a substantial voltage input to maintain consistent functionality. Sustaining this high voltage throughout the operational period presents a formidable challenge. Moreover, ED operations demand a significant amount of energy, typically ranging from 6 to 11 kWh/m^3 [205]. Large-scale ED treatment facilities tasked with processing hundreds of tons of wastewater per day, especially with high salinity feed solutions, can consume as much as 6.4 kWh per kilogram. To address this challenge, as proposed by Chen et al., the introduction of resins to form conductive chains and expedite ion transportation has proven to be an effective method for enhancing the electrical conductivity of the solution. Their research revealed that the inclusion of resins in the ED stack chambers resulted in a substantial reduction in energy consumption, lowering it from 5.6 kWh/kg to 0.6 kWh/kg for recovered materials [237].

The efficient removal of ions, particularly those present in low concentrations alongside high concentration ions in seawater, brine, or geothermal fluids, often poses a significant challenge. This challenge can be surmounted by introducing highly selective membranes into the Electrodialysis (ED) system, as suggested by reference [238]. White et al. conducted an experiment to evaluate the selectivity of membranes coated with polyelectrolyte multilayers, with the objective of assessing the feasibility of these membranes for highly selective separations in electrodialysis. Their findings indicate that membrane selectivity can indeed be enhanced through modification, albeit with the caveat that the stability of the films may be compromised in the presence of strong current fields, despite the associated improvement in selectivity [239].

The affordability of Electrodialysis (ED) technologies represents a significant impediment to their widespread adoption. In order to become more universally accessible, these technologies must demonstrate cost-effectiveness, operational simplicity, and treatment efficiency on par with conventional treatment methods, as highlighted by reference [59]. An analysis has revealed the costs associated with recovering various acids and alkalis, such as \$1.69/kg for NaOH, \$0.5446/kg for Na2SO4, \$0.937/kg for H3PO2, \$0.49/kg for HCl, \$2.243/kg for LiOH, and \$1.304/kg for HCOOH [237]. The cost of energy in the ED process can be reduced by the implementation of hybrid technologies as suggested by Zoungrana et al. in their recent experiment of harvesting salinity gradient power using RED integrated with ED [240].

4. Conclusion

ED is a key technology for achieving a CRE in WIN by desalination and resource recovery. A closed-loop system can be established in WIN based on ED, highlighting the interconnectedness of various components and processes related to WIN. A comprehensive water management system can be ensured starting with the generation of wastewater and subsequent flowing of wastewater through different stages, emphasizing the concept of circularity. The treated wastewater undergoes ED desalination leading to the production of desalinated water. The desalinated water will serve as a valuable resource for WIN to different sectors such as industrial processes, agriculture, and municipalities, to name but a few. This demonstrates the potential for water recovery and reuse, contributing to a more sustainable water management approach. The concentrated brine, a residual stream from the desalination process, undergoes selective electrodialysis and reverse electrodialysis. These processes enable the extraction of valuable compounds and facilitate energy generation, respectively. The conversion of the brine to value-added products and hydrogen fuel symbolizes the utilization of these recovered resources, further enhancing the circular economy aspect. The key message of this review paper emphasises the role of sustainable ED desalination in enabling water recovery, resource efficiency, energy recovery and the generation of value-added products. It presented the interrelation between wastewater treatment, desalination, resource recovery, and circular economy in water industries. Sustainable EDDRR could produce pure water, nutrients, energy recovery, especially hydrogen, oxygen, electricity, metals and ions and value-added products for a CRE in the WIN. This review paper comprehensively, systematically, and critically assessed the sustainability of EDDRR, which is the first comprehensive assessment of EDDRR in WIN for a closed-loop economy. The significant insights of this study could be essential for the development of a sustainable CRE-based EDDRR process for WIN to attain sustainable development goals (SDGs), especially SDGs 6,7,9,11 and 13, by utilizing ED technologies.

CRediT authorship contribution statement

Mohammad Mahbub Kabir: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Validation, Writing-original draft; **Golam Md. Sabur**: Formal analysis, Data curation, Validation, Writing-review & editing; **Mst. Mahmoda Akter:** Formal analysis, Data curation, Validation, Writing-review & editing; **Sang Yong Nam:** Validation, Writing-review & editing; **Kwang Seop Im:** Validation, Writing-review & editing; **Leonard Tijing:** Supervision, Data curation, Validation, Writing-review & editing; **Ho Kyong Shon:** Conceptualization, Supervision, Project administration, Resources, Funding acquisition, Validation, Writing- review & editing.

Acknowledgments

This project was supported by the Australian Research Council (ARC) through the ARC Research Hub for Nutrients in a Circular Economy (NiCE) (IH210100001) and Korea Institute for Advancement of Technology (KIAT) grant funded by the Korea Government (MOTIE) (P0017310, Human Resource Development Program for Industrial Innovation (Global). M. M. Kabir is grateful for the financial support from the International Research Scholarship (IRS) and UTS President's Scholarship (UTSP) for his PhD studies.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available upon request to corresponding author.

References

1. M. Elgallal, L. Fletcher, B. Evans, Assessment of potential risks associated with chemicals in wastewater used for irrigation in arid and semiarid zones: a review, Agric. Water Manag. 177 (2016) 419–431, https://doi.org/10.1016/j.agwat.2016.08.027.
2. C.F. Carolin, P.S. Kumar, A. Saravanan, G.J. Joshiba, M. Naushad, Efficient techniques for the removal of toxic heavy metals from aquatic environment: a review, J. Environ. Chem. Eng. 5 (2017) 2782–2799, https://doi.org/10.1016/j.jece.2017.05.029.
3. P.F. Tee, M.O. Abdullah, I.A.W. Tan, N.K.A. Rashid, M.A.M. Amin, C. Nolasco-Hipolito, K. Bujang, Review on hybrid energy systems for wastewater treatment and bio-energy production, Renew. Sustain. Energy Rev. 54 (2016) 235–246, https://doi.org/10.1016/j.rser.2015.10.011.
4. M.B. Ahmed, J.L. Zhou, H.H. Ngo, W. Guo, N.S. Thomaidis, J. Xu, Progress in the biological and chemical treatment technologies for emerging contaminant removal from wastewater: a critical review, J. Hazard. Mater. 323 (2017) 274–298, https://doi.org/10.1016/j.jhazmat.2016.04.045.
5. S.O. Ganiyu, E.D. Van Hullebusch, M. Cretin, G. Esposito, M.A. Oturan, Coupling of membrane filtration and advanced oxidation processes for removal of pharmaceutical residues: a critical review, Sep. Purif. Technol. 156 (2015) 891–914, https://doi.org/10.1016/j.seppur.2015.09.059.
6. E.M. Carstea, J. Bridgeman, A. Baker, D.M. Reynolds, Fluorescence spectroscopy for wastewater monitoring: a review, Water Res. 95 (2016) 205–219, https://doi.org/10.1016/j.watres.2016.03.021.
7. M.M. Kabir, M.M. Akter, Z. Huang, L. Tijing, H.K. Shon, Hydrogen production from water industries for a circular economy. Desalination, 554 (2023), 116448, https://doi.org/10.1016/j.desal.2023.116448

8. S. Honarparvar, R. Al-Rashed, A comprehensive investigation of performance of pulsed electrodialysis for desalination of brackish water, Desalination, 547(2023), 116240, https://doi.org/10.1016/j.desal.2022.116240.
9. B. M. An, S. L. Aung, J. Choi, H. Cha, J. Cho, B. Byambaa, K. G. Song, Behavior of solutes and membrane fouling in an electrodialysis to treat a side-stream: Migration of ions, dissolved organics and micropollutants, Desalination, 549 (2023), 116361, https://doi.org/10.1016/j.desal.2022.116361
10. X. Wang, J. Liu, Z. Ji, Y. Zhao, F. Li, X. Guo, J. Yuan, Cost and exergy analysis on integrated process of electrodialysis metathesis-reverse osmosis-evaporation for producing K_2SO_4 from Na_2SO_4, Desalination, 550 (2023), 116384, https://doi.org/10.1016/j.desal.2023.116384
11. Filingeri, L. Gurreri, M. Ciofalo, A. Cipollina, A. Tamburini, G. Micale, Current distribution along electrodialysis stacks and its influence on the current-voltage curve: behavior from near-zero current to limiting plateau, Desalination, 556 (2023), 116541, https://doi.org/10.1016/j.desal.2023.116541.
12. G. Campisi, A. Cosenza, F. Giacalone, S. Randazzo, A. Tamburini, G. Micale, Desalination of oilfield produced waters via reverse electrodialysis: a techno-economical assessment, Desalination, 548 (2023), 116289, https://doi.org/10.1016/j.desal.2022.116289.
13. J. Mustafa, A. H. Al-Marzouqi, N. Ghasem, M. H. El-Naas, B. Van der Bruggen, Electrodialysis process for carbon dioxide capture coupled with salinity reduction: A statistical and quantitative investigation, Desalination, 548 (2023), 116263, https://doi.org/10.1016/j.desal.2022.116263.
14. J. Chen, J. Wang, Z. Ji, Y. Guo, Z. Zhang, Z. Huang, Electro-nanofiltration membranes with high Li^+/Mg^{2+} selectivity prepared via sequential interfacial polymerization, Desalination, 549 (2023), 116312, https://doi.org/10.1016/j.desal.2022.116312.
15. M. Sedighi, M. M. Usefi, B. Ismail, M. Ghasemi, Environmental sustainability and ions removal through electrodialysis desalination: operating conditions and process parameters, Desalination, 549 (2023), 116319, https://doi.org/10.1016/j.desal.2022.116319
16. P. Kovar, M. Smolen, J. Pagac, M. Kincl, Z. Slouka, Experimental 3D concentration profiles along an electrodialysis channel reveal a strong effect of natural convection, Desalination, 548 (2023), 116302, https://doi.org/10.1016/j.desal.2022.116302

17. J. Liao, J. Xu, H. Ruan, J. Mu, X. Jie, W. Li, J. Shen, Exploring the organic solvent resistance of anion exchange membranes based on poly (2, 6-dimethyl-1, 4-phenyl oxide) for electrodialysis desalination, Desalination, 546 (2023), 116202, https://doi.org/10.1016/j.desal.2022.116202.
18. J. N. Easley, S. Talozi, Feasibility and design of solar-powered electrodialysis reversal desalination systems for agricultural applications in the Middle East and North Africa, Desalination, 561 (2023), 116628, https://doi.org/10.1016/j.desal.2023.116628.
19. J. Wang, M. Liu, Z. Feng, J. Liu, S. Liao, X. Li, Y. Yu, Highly conductive anion exchange membrane with a stable double-sided anti-fouling structure for electrodialysis desalination of protein systems, Desalination, 545 (2023), 116167, https://doi.org/10.1016/j.desal.2022.116167
20. H. Zhang, Y. Li, J. Han, Y. Sun, M. He, Z. Hao, M. Liu, Influence of ion exchange membrane arrangement on dual-channel flow electrode capacitive deionization: Theoretical analysis and experimentations, Desalination, 548 (2023), 116288, https://doi.org/10.1016/j.desal.2022.116288
21. S. Honarparvar, R. Al-Rashed, Investigation of pulsed electric field operation as a chemical-free anti-scaling approach for electrodialysis desalination of brackish water, Desalination, 551 (2023), 116386, https://doi.org/10.1016/j.desal.2023.116386
22. H. Tang, X. Wang, X. Zhao, Y. Dong, B. Xu, L. Wang, Ion migration characteristics during the bipolar membrane electrodialysis treatment of concentrated reverse osmosis brine, Desalination, 561(2023), 116660, https://doi.org/10.1016/j.desal.2023.116660
23. J. Yan, H. Wang, H. Yan, R. Li, R. Fu, W. Fu, T. Xu, Ion transmembrane behaviors in selective electrodialysis for acid recovery: impact of ion categories, Desalination, 554 (2023), 116513, https://doi.org/10.1016/j.desal.2023.116513.
24. P. Zimmermann, O. Tekinalp, S. B. B. Solberg, O. Wilhelmsen, L. Deng, O. S. Burheim, Limiting current density as a selectivity factor in electrodialysis of multi-ionic mixtures, Desalination, 558 (2023), 116613, https://doi.org/10.1016/j.desal.2023.116613.
25. V. Kovalenko, V. V. Nikonenko, N. O. Chubyr, M. K. Urtenov, Mathematical modeling of electrodialysis of a dilute solution with accounting for water dissociation-recombination reactions, Desalination, 550 (2023), 116398, https://doi.org/10.1016/j.desal.2023.116398.

26. D. Yang, H., Liu, Q. She, Mixed cation transport behaviors in electrodialysis during simultaneous ammonium enrichment and wastewater desalination, Desalination, 545(2023), 116155, https://doi.org/10.1016/j.desal.2022.116155.

27. M. Ahmad, M. Ahmed, S. Hussain, A. Ali, M. Zahra, M. I. Din, Z. Mustafa, Polyelectrolyte multilayers coating of aliphatic polyamide anion-exchange membranes to increase monovalent/divalent anions selectivity in electrodialysis, Desalination, 545 (2023), 116159, https://doi.org/10.1016/j.desal.2022.116159.

28. T. Elmakki, S. Zavahir, M. Gulied, H. Qiblawey, B. Hammadi, M. Khraisheh, D. S. Han, Potential application of hybrid reverse electrodialysis (RED)-forward osmosis (FO) system to fertilizer-producing industrial plant for efficient water reuse, Desalination, 550 (2023), 116374, https://doi.org/10.1016/j.desal.2023.116374.

29. M. Aliaskari, R. L. Ramos, A. I. Schafer, Removal of arsenic and selenium from brackish water using electrodialysis for drinking water production. Desalination, 548 (2023), 116298, https://doi.org/10.1016/j.desal.2022.116298.

30. B. Vital, T. Sleutels, M. C. Gagliano, H. V. Hamelers, Reversible fouling by particulate matter from natural seawater reduces RED performance while limiting biofouling, Desalination, 548(2023), 116262, https://doi.org/10.1016/j.desal.2022.116262.

31. J. Ma, C. Zhai, F. Yu, Review of flow electrode capacitive deionization technology: Research progress and future challenges, Desalination, 2023, 116701, https://doi.org/10.1016/j.desal.2023.116701.

32. Siekierka, D. L. Calahan, W. Kujawski, L. F. Dumee, Ultra-selective chelating membranes for recycling of cobalt from lithium-ion spent battery effluents by electrodialysis, Desalination, 556 (2023), 116561, https://doi.org/10.1016/j.desal.2023.116561

33. Y. Lan, Y. Huang, H. Qi, L. Lai, L. Xia, Z. Zhao, Y. Zhao, Alternating electric field-based ionic control and layer-by-layer assembly of anion exchange membranes for enhancing target anion selectivity, Desalination, 533(2022), 115773, https://doi.org/10.1016/j.desal.2022.115773.

34. Q. B. Chen, Y. Xu, P. F. Li, J. Wang, L. Dong, J. Zhao, J. Wang, An emerging pilot-scale electrodialysis system for desalination of SWNF permeate: Evaluating the role of typical factors, Desalination, 542 (2022), 116064, https://doi.org/10.1016/j.desal.2022.116064.

35. F. Deboli, B. Van der Bruggen, M. L. Donten, A versatile chemistry platform for the fabrication of cost-effective hierarchical cation and anion exchange membranes. Desalination, 535 (2022), 115794, https://doi.org/10.1016/j.desal.2022.115794

36. J. Ledingham, K. L. S. Campbell, L. Keyzer, A. N. Campbell, Barriers to electrodialysis implementation: Maldistribution and its impact on resistance and limiting current density, Desalination, 531(2022), 115691, https://doi.org/10.1016/j.desal.2022.115691.

37. W. Xia, Y. Yang, X. Shang, X. Yang, S. Wang, F. Gong, X. Chen, Cardopoly (arylene ether sulfone) s membranes bearing N-cyclic cationic groups enable high performance during both diffusion dialysis and electrodialysis, Desalination, 529 (2022), 115646, https://doi.org/10.1016/j.desal.2022.115646

38. L. Gurreri, M. La Cerva, J. Moreno, B. Goossens, A. Trunz, A. Tamburini, Coupling of electro-membrane processes with reverse osmosis for seawater desalination: Pilot plant demonstration and testing. Desalination, 526 (2022), 115541, https://doi.org/10.1016/j.desal.2021.115541.

39. X. Sun, M. Di, L. Gao, L. Hu, W. Zheng, X. Ruan, G. He, Covalent organic framework-based membrane improved the performance of reverse electrodialysis under Na^+/Mg^{2+} mixed solution, Desalination, 542 (2022), 115976, https://doi.org/10.1016/j.desal.2022.115976.

40. C. G. Patel, D. Barad, J. Swaminathan, Desalination using pressure or electric field? A fundamental comparison of RO and electrodialysis, Desalination, 530 (2022), 115620, https://doi.org/10.1016/j.desal.2022.115620.

41. Q. Xia, Z. Zhou, X. Zhao, M. Zhang, C. Wu, S. Yu, G. Liu, Effects of calcium ions on anionic polyacrylamide fouling of ion-exchange membranes in desalination of polymer-flooding wastewater by electrodialysis, Desalination, 535 (2022), 115846, https://doi.org/10.1016/j.desal.2022.115846.

42. K. Morita, T. Matsumoto, T. Hoshino, Efficient lithium extraction via electrodialysis using acid-processed lithium-adsorbing lithium lanthanum titanate, Desalination, 543(2022), 116117, https://doi.org/10.1016/j.desal.2022.116117.

43. Y. Cao, M. Kasaeian, H. Abbasspoor, M. Shamoushaki, M. A. Ehyaei, S. Abanades, Energy, exergy, and economic analyses of a novel biomass-based multigeneration system integrated with multi-effect distillation, electrodialysis, and LNG tank, Desalination, 526 (2022), 115550, https://doi.org/10.1016/j.desal.2022.115550.

44. Y. Liu, Y. Sun, Z. Peng, Evaluation of bipolar membrane electrodialysis for desalination of simulated salicylic acid wastewater, Desalination, 537 (2022), 115866, https://doi.org/10.1016/j.desal.2022.115866.
45. J. H. Han, Experimental visualization of leakage current in reverse electrodialysis and its effect on inorganic scaling, Desalination, 527 (2022), 115584, https://doi.org/10.1016/j.desal.2022.115584.
46. Y. Xu, Q. B. Chen, J. Wang, P. F. Li, J. Zhao, Fractionation of monovalent ions from seawater brine via softening nanofiltration and selective electrodialysis: which is better? Desalination, 533 (2022), 115717, https://doi.org/10.1016/j.desal.2022.115717.
47. E. Altıok, T. Z. Kaya, N. H. Othman, O. Kınalı, S. Kitada, E. Guler, N. Kabay, Investigations on the effects of operational parameters in reverse electrodialysis system for salinity gradient power generation using central composite design (CCD), Desalination, 525(2022), 115508, https://doi.org/10.1016/j.desal.2021.115508.
48. J. Yan, H. Wang, R. Fu, R. Fu, R. Li, B. Chen, T. Xu, Ion exchange membranes for acid recovery: diffusion dialysis (DD) or selective electrodialysis (SED)? Desalination, 531 (2022), 115690, https://doi.org/10.1016/j.desal.2022.115690.
49. X. Wang, Y. Du, J. Liu, F. Xu, Z. Ji, X. Guo, J. Yuan, Modeling and simulation of continuous electrodialysis metathesis process for conversion of Na_2SO_4 to K_2SO_4. Desalination, 528 (2022), 115605, https://doi.org/10.1016/j.desal.2022.115605.
50. Q. B. Chen, Z. Tian, J. Zhao, J. Wang, P. F. Li, Y. Xu, Near-zero liquid discharge and reclamation process based on electrodialysis metathesis for high-salinity wastewater with high scaling potential, Desalination, 525 (2022), 115390, https://doi.org/10.1016/j.desal.2021.115390.
51. D. Y. Butylskii, V. A. Troitskiy, M. V. Sharafan, N. D. Pismenskaya, V. V. Nikonenko, Scaling-resistant anion-exchange membrane prepared by in situ modification with a bifunctional polymer containing quaternary amino groups, Desalination, 537 (2022), 115821, https://doi.org/10.1016/j.desal.2022.115821.
52. H. Sun, A. Li, P. Shi, X. Cao, C. Wang, S. Cheng, (2022) Separation of NaCl and humic substances in anion exchange spent brine with electrodialysis, Desalination, 523 (2022), 115442, https://doi.org/10.1016/j.desal.2021.115442.
53. D. V. Golubenko, A. D. Manin, Y. Wang, T. Xu, A. B. Yaroslavtsev, The way to increase the monovalent ion selectivity of FujiFilm® anion-exchange membranes by cerium phosphate modification for electrodialysis desalination, Desalination, 531 (2022), 115719, https://doi.org/10.1016/j.desal.2022.115719.

54. F. Dong, D. Jin, S. Xu, X. Wu, P. Wang, D. Wu, R. Xi, Three-dimensional multi-physical simulation of a reverse electrodialysis stack with profiled membranes, Desalination, 537 (2022), 115894, https://doi.org/10.1016/j.desal.2022.115894.

55. M. N. Z. Abidin, M. M., Nasef, J. Veerman, Towards the development of new generation of ion exchange membranes for reverse electrodialysis: a review, Desalination, 537 (2022), 115854, https://doi.org/10.1016/j.desal.2022.115854.

56. Q. B. Chen, P. F. Li, J. Wang, Y. Xu, J. Wang, L. Dong, J. Zhao, Transport of salts and monoethylene glycol (MEG) during electrodialysis desalination of industrial hypersaline MEG wastewater, Desalination, 530(2022), 115683, https://doi.org/10.1016/j.desal.2022.115683.

57. A., Filingeri, M., Philibert, E., Filloux, N., Moe, A., Poli, A., Tamburini, A. Cipollina, Valorization of surface-water RO brines via Assisted-Reverse Electrodialysis for minerals recovery: Performance analysis and scale-up perspectives, Desalination, 541 (2022), 116036, https://doi.org/10.1016/j.desal.2022.116036.

58. L. Gurreri, A. Tamburini, A. Cipollina, G. Micale, Electrodialysis applications in wastewater treatment for environmental protection and resources recovery: a systematic review on progress and perspectives, Membranes, 10 (2020), 146, https://doi.org/10.3390/membranes10070146

59. R. Mohammadi, W. Tang, M. Sillanpää, A systematic review and statistical analysis of nutrient recovery from municipal wastewater by electrodialysis, Desalination. 498 (2021). https://doi.org/10.1016/j.desal.2020.114626.

60. S. Thampy, G.R. Desale, V.K. Shahi, B.S. Makwana, P.K. Ghosh, Development of hybrid electrodialysis-reverse osmosis domestic desalination unit for high recovery of product water, Desalination. 282 (2011) 104–108. https://doi.org/10.1016/j.desal.2011.08.060.

61. R. Mohammadi, D.L. Ramasamy, M. Sillanpaa, Enhancement of nitrate removal and recovery from municipal wastewater through single-and multi-batch electrodialysis: process optimization and energy consumption, Desalination, 498 (2021), 114726. https://doi.org/10.1016/j.desal.2020.114726.

62. R. Liu, Y. Wang, G. mart, J. Luo, S. Wang, Development of a selective electrodialysis for nutrient recovery and desalination during secondary effluent treatment, Chemical Engineering Journal. 322 (2017) 224–233. https://doi.org/10.1016/j.cej.2017.03.149.

63. M. Xie, H.K. Shon, S.R. Gray, M. Elimelech, Membrane-based processes for wastewater nutrient recovery: Technology, challenges, and future direction, Water Res. 89 (2016) 210–221. https://doi.org/10.1016/j.watres.2015.11.045.

64. M. Mondor, L. Masse, D. Ippersiel, F. Lamarche, D.I. Massé, Use of electrodialysis and reverse osmosis for the recovery and concentration of ammonia from swine manure, Bioresour Technol. 99 (2008) 7363–7368. https://doi.org/10.1016/j.biortech.2006.12.039.

65. V. Oliveira, C. Dias-Ferreira, I. González-García, J. Labrincha, C. Horta, M.C. García-González, A novel approach for nutrients recovery from municipal waste as biofertilizers by combining electrodialytic and gas permeable membrane technologies, Waste Management. 125 (2021) 293–302. https://doi.org/10.1016/j.wasman.2021.02.055.

66. K.C. Kedwell, M.K. Jørgensen, C.A. Quist-Jensen, T.D. Pham, B. Van der Bruggen, M.L. Christensen, Selective electrodialysis for simultaneous but separate phosphate and ammonium recovery, Environmental Technology (United Kingdom). 42 (2021) 2177–2186. https://doi.org/10.1080/09593330.2019.1696410.

67. X. Vecino, M. Reig, O. Gibert, C. Valderrama, J.L. Cortina, Integration of liquid-liquid membrane contactors and electrodialysis for ammonium recovery and concentration as a liquid fertilizer, Chemosphere. 245 (2020). https://doi.org/10.1016/j.chemosphere.2019.125606.

68. Z.L. Ye, K. Ghyselbrecht, A. Monballiu, L. Pinoy, B. Meesschaert, Fractionating various nutrient ions for resource recovery from swine wastewater using simultaneous anionic and cationic selective-electrodialysis, Water Research. 160 (2019) 424–434. https://doi.org/10.1016/j.watres.2019.05.085.

69. J. De Paepe, R.E.F. Lindeboom, M. Vanoppen, K. De Paepe, D. Demey, W. Coessens, B. Lamaze, A.R.D. Verliefde, P. Clauwaert, S.E. Vlaeminck, Refinery and concentration of nutrients from urine with electrodialysis enabled by upstream precipitation and nitrification, Water Res. 144 (2018) 76–86. https://doi.org/10.1016/j.watres.2018.07.016.

70. Y.K. Wang, Y.K. Geng, X.R. Pan, G.P. Sheng, In situ utilization of generated electricity for nutrient recovery in urine treatment using a selective electrodialysis membrane bioreactor, Chem Eng Sci. 171 (2017) 451–458. https://doi.org/10.1016/j.ces.2017.06.002.

71. F. Gao, L. Wang, J. Wang, H. Zhang, S. Lin, Nutrient recovery from treated wastewater by a hybrid electrochemical sequence integrating bipolar membrane electrodialysis and membrane capacitive deionization, Environ Sci (Camb). 6 (2020) 383–391. https://doi.org/10.1039/C9EW00981G.

72. L. Shi, Y. Hu, S. Xie, G. Wu, Z. Hu, X. Zhan, Recovery of nutrients and volatile fatty acids from pig manure hydrolysate using two-stage bipolar membrane electrodialysis, Chemical Engineering Journal. 334 (2018) 134–142. https://doi.org/10.1016/j.cej.2017.10.010.

73. L. Shi, L. Xiao, Z. Hu, X. Zhan, Nutrient recovery from animal manure using bipolar membrane electrodialysis: Study on product purity and energy efficiency, Water Cycle. 1 (2020) 54–62. https://doi.org/10.1016/j.watcyc.2020.06.002.

74. A.J. Ward, K. Arola, E. Thompson Brewster, C.M. Mehta, D.J. Batstone, Nutrient recovery from wastewater through pilot scale electrodialysis, Water Research. 135 (2018) 57–65. https://doi.org/10.1016/j.watres.2018.02.021.

75. L.B.M. Barros, Y.L. Brasil, A.F.R. Silva, L.H. Andrade, M.C.S. Amaral, Potassium recovery from vinasse by integrated electrodialysis – precipitation process: Effect of the electrolyte solutions, J Environ Chem Eng. 8 (2020). https://doi.org/10.1016/j.jece.2020.104238.

76. M. Červenková, J. Chromíková, S. Heviánková, Z. Wranová, The application of electrodialysis for the recovery of phosphorus from wastewater sludge liquid discharge, in: IOP Conf Ser Earth Environ Sci, Institute of Physics Publishing, 2017. https://doi.org/10.1088/1755-1315/92/1/012007.

77. Y. Zhang, B. Van der Bruggen, L. Pinoy, B. Meesschaert, Separation of nutrient ions and organic compounds from salts in RO concentrates by standard and monovalent selective ion-exchange membranes used in electrodialysis, J Memb Sci. 332 (2009) 104–112. https://doi.org/10.1016/j.memsci.2009.01.030.

78. A. Cournoyer, L. Bazinet, Electrodialysis Processes an Answer to Industrial Sustainability: Toward the Concept of Eco-Circular Economy?—A Review, Membranes (Basel). 13 (2023). https://doi.org/10.3390/membranes13020205

79. C. Tristán, M. Fallanza, R. Ibáñez, I. Ortiz, Recovery of salinity gradient energy in desalination plants by reverse electrodialysis, Desalination. 496 (2020). https://doi.org/10.1016/j.desal.2020.114699.

80. B. Vital, E. V. Torres, T. Sleutels, M.C. Gagliano, M. Saakes, H.V.M. Hamelers, Fouling fractionation in reverse electrodialysis with natural feed waters demonstrates dual media rapid filtration as an effective pre-treatment for fresh water, Desalination. 518 (2021). https://doi.org/10.1016/j.desal.2021.115277.

81. O.A. Alvarez-Silva, A.F. Osorio, C. Winter, Practical global salinity gradient energy potential, Renewable and Sustainable Energy Reviews. 60 (2016) 1387–1395. https://doi.org/10.1016/j.rser.2016.03.021.

82. M.C. Hatzell, X. Zhu, B.E. Logan, Simultaneous hydrogen generation and waste acid neutralization in a reverse electrodialysis system, ACS Sustain Chem Eng. 2 (2014) 2211–2216. https://doi.org/10.1021/sc5004133

83. B. Ortega-Delgado, F. Giacalone, P. Catrini, A. Cipollina, A. Piacentino, A. Tamburini, G. Micale, Reverse electrodialysis heat engine with multi-effect distillation: Exergy analysis and perspectives, Energy Convers Manag. 194 (2019) 140–159. https://doi.org/10.1016/j.enconman.2019.04.056.

84. Y.D. Raka, H. Karoliussen, K.M. Lien, O.S. Burheim, Opportunities and challenges for thermally driven hydrogen production using reverse electrodialysis system, Int J Hydrogen Energy. 45 (2020) 1212–1225. https://doi.org/10.1016/j.ijhydene.2019.05.126.

85. Y. Mei, C.Y. Tang, Recent developments and future perspectives of reverse electrodialysis technology: A review, Desalination. 425 (2018) 156–174. https://doi.org/10.1016/j.desal.2017.10.021.

86. D. Jin, R. Xi, S. Xu, P. Wang, X. Wu, Numerical simulation of salinity gradient power generation using reverse electrodialysis, Desalination. 512 (2021). https://doi.org/10.1016/j.desal.2021.115132.

87. M. Roldan-Carvajal, S. Vallejo-Castaño, O. Álvarez-Silva, S. Bernal-García, S. Arango-Aramburo, C.I. Sánchez-Sáenz, A.F. Osorio, Salinity gradient power by reverse electrodialysis: A multidisciplinary assessment in the Colombian context, Desalination. 503 (2021). https://doi.org/10.1016/j.desal.2021.114933.

88. E.H. Hossen, Z.E. Gobetz, R.S. Kingsbury, F. Liu, H.C. Palko, L.L. Dubbs, O. Coronell, D.F. Call, Temporal variation of power production via reverse electrodialysis using coastal North Carolina waters and its correlation to temperature and conductivity, Desalination. 491 (2020). https://doi.org/10.1016/j.desal.2020.114562.

89. F. Luo, Y. Wang, C. Jiang, B. Wu, H. Feng, T. Xu, A power free electrodialysis (PFED) for desalination, Desalination. 404 (2017) 138–146. https://doi.org/10.1016/j.desal.2016.11.011.

90. J. Jang, Y. Kang, J.H. Han, K. Jang, C.M. Kim, I.S. Kim, Developments and future prospects of reverse electrodialysis for salinity gradient power generation: Influence of ion exchange membranes and electrodes, Desalination. 491 (2020). https://doi.org/10.1016/j.desal.2020.114540.

91. K. Chon, N. Jeong, H. Rho, J.Y. Nam, E. Jwa, J. Cho, Fouling characteristics of dissolved organic matter in fresh water and seawater compartments of reverse electrodialysis under natural water conditions, Desalination. 496 (2020). https://doi.org/10.1016/j.desal.2020.114478.

92. R. Long, Y. Zhao, Z. Kuang, Z. Liu, W. Liu, Hydrodynamic slip enhanced nanofluidic reverse electrodialysis for salinity gradient energy harvesting, Desalination. 477 (2020). https://doi.org/10.1016/j.desal.2019.114263.

93. I. Atlas, M.E. Suss, Theory of simultaneous desalination and electricity generation via an electrodialysis cell driven by spontaneous redox reactions, Electrochim Acta. 319 (2019) 813–821. https://doi.org/10.1016/j.electacta.2019.06.014.

94. A.A. Filimonova, A.A. Chichirov, N.D. Chichirova, The Utilization of Highly Mineralized Liquid Waste from a Chemical Desalination Water Treatment Plant of a TPP with the Generation of Electrical Energy by Reverse Electrodialysis, Membranes and Membrane Technologies. 3 (2021) 344–350. https://doi.org/10.1134/S251775162105005X.

95. M. Tedesco, A. Cipollina, A. Tamburini, G. Micale, J. Helsen, M. Papapetrou, REAPower: use of desalination brine for power production through reverse electrodialysis, Desalination Water Treat. 53 (2015) 3161–3169. https://doi.org/10.1080/19443994.2014.934102

96. A. Tamburini, M. Tedesco, A. Cipollina, G. Micale, M. Ciofalo, M. Papapetrou, W. Van Baak, A. Piacentino, Reverse electrodialysis heat engine for sustainable power production, Appl Energy. 206 (2017) 1334–1353. https://doi.org/10.1016/j.apenergy.2017.10.008.

97. F. Giacalone, F. Vassallo, F. Scargiali, A. Tamburini, A. Cipollina, G. Micale, The first operating thermolytic reverse electrodialysis heat engine, J Memb Sci. 595 (2020). https://doi.org/10.1016/j.memsci.2019.117522.

98. F. Giacalone, F. Vassallo, L. Griffin, M.C. Ferrari, G. Micale, F. Scargiali, A. Tamburini, A. Cipollina, Thermolytic reverse electrodialysis heat engine: model development, integration and performance analysis, Energy Convers Manag. 189 (2019) 1–13. https://doi.org/10.1016/j.enconman.2019.03.045.

99. J.Y. Nam, R.D. Cusick, Y. Kim, B.E. Logan, Hydrogen generation in microbial reverse-electrodialysis electrolysis cells using a heat-regenerated salt solution, Environ Sci Technol. 46 (2012) 5240–5246. https://doi.org/10.1021/es300228m.

100. Y. Kim, B.E. Logan, Hydrogen production from inexhaustible supplies of fresh and salt water using microbial reverse-electrodialysis electrolysis cells, Proc Natl Acad Sci U S A. 108 (2011) 16176–16181. https://doi.org/10.1073/pnas.1106335108.

101. S. Hidayat, Y.H. Song, J.Y. Park, A comparison of mono- and multi-valent ions as stack feed solutions in microbial reverse-electrodialysis electrolysis cells and their effects on hydrogen generation, Int Biodeterior Biodegradation. 113 (2016) 28–33. https://doi.org/10.1016/j.ibiod.2016.03.008.

102. J. Tang, S. Jia, S. Qu, Y. Xiao, Y. Yuan, N.Q. Ren, An integrated biological hydrogen production process based on ethanol-type fermentation and bipolar membrane electrodialysis, in: Int J Hydrogen Energy, Elsevier Ltd, 2014: pp. 13375–13380. https://doi.org/10.1016/j.ijhydene.2014.04.085.

103. M.C. Hatzell, I. Ivanov, R. D. Cusick, X. Zhu, B.E. Logan, Comparison of hydrogen production and electrical power generation for energy capture in closed-loop ammonium bicarbonate reverse electrodialysis systems, Physical Chemistry Chemical Physics. 16 (2014) 1632–1638. https://doi.org/10.1039/c3cp54351j.

104. M. Nazemi, J. Zhang, M.C. Hatzell, Harvesting Natural Salinity Gradient Energy for Hydrogen Production Through Reverse Electrodialysis Power Generation, Journal of

Electrochemical Energy Conversion and Storage. 14 (2017). https://doi.org/10.1115/1.4035835.

105. R.A. Tufa, E. Rugiero, D. Chanda, J. Hnàt, W. van Baak, J. Veerman, E. Fontananova, G. Di Profio, E. Drioli, K. Bouzek, E. Curcio, Salinity gradient power-reverse electrodialysis and alkaline polymer electrolyte water electrolysis for hydrogen production, J Memb Sci. 514 (2016) 155–164. https://doi.org/10.1016/j.memsci.2016.04.067.

106. Magro, C., Almeida, J., Paz-Garcia, J. M., Mateus, E. P., & Ribeiro, A. B. (2019). Exploring hydrogen production for self-energy generation in electroremediation: A proof of concept. Applied Energy, 255, 113839. https://doi.org/10.1016/j.apenergy.2019.113839

107. J.M. Arana Juve, F.M.S. Christensen, Y. Wang, Z. Wei, Electrodialysis for metal removal and recovery: A review, Chemical Engineering Journal. 435 (2022). https://doi.org/10.1016/j.cej.2022.134857.

108. A. Siekierka, M. Bryjak, A. Razmjou, W. Kujawski, A.N. Nikoloski, L.F. Dumée, Electro-Driven Materials and Processes for Lithium Recovery—A Review, Membranes (Basel). 12 (2022). https://doi.org/10.3390/membranes12030343.

109. A. Güvenç, B. Karabacakoğlu, Use of electrodialysis to remove silver ions from model solutions and wastewater, Desalination. 172 (2005) 7–17. https://doi.org/10.1016/j.desal.2004.06.193.

110. J.X. Zhuang, Q. Chen, S. Wang, W.M. Zhang, W.G. Song, L.J. Wan, K.S. Ma, C.N. Zhang, Zero discharge process for foil industry waste acid reclamation: Coupling of diffusion dialysis and electrodialysis with bipolar membranes, J Memb Sci. 432 (2013) 90–96. https://doi.org/10.1016/j.memsci.2013.01.016.

111. M.T. Pham, S. Nishihama, K. Yoshizuka, Effect of Operational Conditions on Arsenic Removal from Aqueous Solution Using Electrodialysis, Solvent Extraction and Ion Exchange. 39 (2021) 655–667. https://doi.org/10.1080/07366299.2021.1876987.

112. R.M.O. Mendoza, C.C. Kan, S.S. Chuang, S.M.B. Pingul-Ong, M.L.P. Dalida, M.W. Wan, Feasibility studies on arsenic removal from aqueous solutions by electrodialysis, J Environ Sci Health A Tox Hazard Subst Environ Eng. 49 (2014) 545–554. https://doi.org/10.1080/10934529.2014.859035.

113. Y.A. Jarma, E. Çermikli, D. İpekçi, E. Altıok, N. Kabay, Comparison of two electrodialysis stacks having different ion exchange and bipolar membranes for simultaneous separation of boron and lithium from aqueous solution, Desalination. 500 (2021). https://doi.org/10.1016/j.desal.2020.114850.

114. M. Turek, Dual-purpose desalination-salt production electrodialysis, Desalination. 153 (2003) 377-381. https://doi.org/10.1016/S0011-9164(02)01131-1

115. Y. Zhao, L. Wang, Z. Ji, J. Liu, X. Guo, F. Li, S. Wang, J. Yuan, Collaborative disposal of problematic calcium ions in seawater and carbon and sulfur pollutants in flue gas by bipolar

membrane electrodialysis, Desalination. 494 (2020). https://doi.org/10.1016/j.desal.2020.114654.

116. M. Reig, S. Casas, O. Gibert, C. Valderrama, J.L. Cortina, Integration of nanofiltration and bipolar electrodialysis for valorization of seawater desalination brines: Production of drinking and waste water treatment chemicals, Desalination. 382 (2016) 13–20. https://doi.org/10.1016/j.desal.2015.12.013.

117. L. Marder, A.M. Bernardes, J. Zoppas Ferreira, Cadmium electroplating wastewater treatment using a laboratory-scale electrodialysis system, Sep Purif Technol. 37 (2004) 247–255. https://doi.org/10.1016/j.seppur.2003.10.011.

118. M.R. Jakobsen, J. Fritt-Rasmussen, S. Nielsen, L.M. Ottosen, Electrodialytic removal of cadmium from wastewater sludge, J Hazard Mater. 106 (2004) 127–132. https://doi.org/10.1016/j.jhazmat.2003.10.005.

119. A. Smara, R. Delimi, C. Poinsignon, J. Sandeaux, Electroextraction of heavy metals from diluted solutions by a process combining ion-exchange resins and membranes, Sep Purif Technol. 44 (2005) 271–277. https://doi.org/10.1016/j.seppur.2005.02.003.

120. L. Marder, G.O. Sulzbach, A.M. Bernardes, J.Z. Ferreira, Removal of Cadmium and Cyanide from Aqueous Solutions through Electrodialysis, Journal of the Brazilian Chemical Society. 14 (2003). https://doi.org/10.1590/S0103-50532003000400018

121. C. Mahendra, P.M. Satya Sai, C. Anand Babu, Current-voltage characteristics in a hybrid electrodialysis-ion exchange system for the recovery of cesium ions from ammonium molybdophosphate-polyacrylonitrile, Desalination. 353 (2014) 8–14. https://doi.org/10.1016/j.desal.2014.08.025.

122. C.S.L. Dos Santos, M.H. Miranda Reis, V.L. Cardoso, M.M. De Resende, Electrodialysis for removal of chromium (VI) from effluent: Analysis of concentrated solution saturation, J Environ Chem Eng. 7 (2019). https://doi.org/10.1016/j.jece.2019.103380.

123. A. Mahmoud, A.F.A. Hoadley, An evaluation of a hybrid ion exchange electrodialysis process in the recovery of heavy metals from simulated dilute industrial wastewater, Water Res. 46 (2012) 3364–3376. https://doi.org/10.1016/j.watres.2012.03.039.

124. Ü.B. Ögütveren, S. Koparal, E. Özel, Electrodialysis for the removal of copper ions from wastewater, J Environ Sci Health A Tox Hazard Subst Environ Eng. 32 (1997) 749–761. https://doi.org/10.1080/10934529709376574.

125. Y.N. Su, W.S. Lin, C.H. Hou, W. Den, Performance of integrated membrane filtration and electrodialysis processes for copper recovery from wafer polishing wastewater, Journal of Water Process Engineering. 4 (2014) 149–158. https://doi.org/10.1016/j.jwpe.2014.09.012.

126. C. Peng, Y. Liu, J. Bi, H. Xu, A.S. Ahmed, Recovery of copper and water from copper-electroplating wastewater by the combination process of electrolysis and electrodialysis, J Hazard Mater. 189 (2011) 814–820. https://doi.org/10.1016/j.jhazmat.2011.03.034.

127. L. Cifuentes, I. García, P. Arriagada, J.M. Casas, The use of electrodialysis for metal separation and water recovery from CuSO4-H2SO4-Fe solutions, Sep Purif Technol. 68 (2009) 105–108. https://doi.org/10.1016/j.seppur.2009.04.017.

128. A. Chekioua, R. Delimi, Purification of H2SO4 of Pickling Bath Contaminated by Fe(II) Ions Using Electrodialysis Process, in: Energy Procedia, Elsevier Ltd, 2015: pp. 1418–1433. https://doi.org/10.1016/j.egypro.2015.07.789.

129. X. Zhang, C. Li, X. Wang, Y. Wang, T. Xu, Recovery of hydrochloric acid from simulated chemosynthesis aluminum foils wastewater: An integration of diffusion dialysis and conventional electrodialysis, J Memb Sci. 409–410 (2012) 257–263. https://doi.org/10.1016/j.memsci.2012.03.062.

130. M. Reig, S. Casas, C. Valderrama, O. Gibert, J.L. Cortina, Integration of monopolar and bipolar electrodialysis for valorization of seawater reverse osmosis desalination brines: Production of strong acid and base, Desalination. 398 (2016) 87–97. https://doi.org/10.1016/j.desal.2016.07.024.

131. X. Wang, J. Liu, Z. Ji, Y. Zhao, F. Li, X. Guo, S. Wang, J. Yuan, Cost and exergy analysis on integrated process of electrodialysis metathesis - reverse osmosis - evaporation for producing K2SO4 from Na2SO4, Desalination. 550 (2023). https://doi.org/10.1016/j.desal.2023.116384.

132. S. Gmar, L. Muhr, F. Lutin, A. Chagnes, Lithium-Ion Battery Recycling: Metal Recovery from Electrolyte and Cathode Materials by Electrodialysis, (2022). https://doi.org/10.3390/met12111859ï.

133. M. Bazrgar Bajestani, A. Moheb, M. Dinari, Preparation of lithium ion-selective cation exchange membrane for lithium recovery from sodium contaminated lithium bromide solution by electrodialysis process, Desalination. 486 (2020). https://doi.org/10.1016/j.desal.2020.114476.

134. P.P. Sharma, V. Yadav, A. Rajput, H. Gupta, H. Saravaia, V. Kulshrestha, Sulfonated poly (ether ether ketone) composite cation exchange membrane for selective recovery of lithium by electrodialysis, Desalination. 496 (2020). https://doi.org/10.1016/j.desal.2020.114755.

135. J. Ying, M. Luo, Y. Jin, J. Yu, Selective separation of lithium from high Mg/Li ratio brine using single-stage and multi-stage selective electrodialysis processes, Desalination. 492 (2020). https://doi.org/10.1016/j.desal.2020.114621.

136. J. shi, J. Yuan, Z. Ji, B. Wang, Y. Hao, X. Guo, Concentrating brine from seawater desalination process by nanofiltration-electrodialysis integrated membrane technology, Desalination. 390 (2016) 53–61. https://doi.org/10.1016/j.desal.2016.03.012.

137. A.K. Singh, M. Bhushan, V.K. Shahi, Alkaline stable thermal responsive cross-linked anion exchange membrane for the recovery of NaOH by electrodialysis, Desalination. 494 (2020). https://doi.org/10.1016/j.desal.2020.114651.

138. T. Benvenuti, M.A. Siqueira Rodrigues, A.M. Bernardes, J. Zoppas-Ferreira, Closing the loop in the electroplating industry by electrodialysis, J Clean Prod. 155 (2017) 130–138. https://doi.org/10.1016/j.jclepro.2016.05.139.

139. T. Benvenuti, R.S. Krapf, M.A.S. Rodrigues, A.M. Bernardes, J. Zoppas-Ferreira, Recovery of nickel and water from nickel electroplating wastewater by electrodialysis, Sep Purif Technol. 129 (2014) 106–112. https://doi.org/10.1016/j.seppur.2014.04.002.

140. T. Mohammadi, A. Razmi, M. Sadrzadeh, Effect of operating parameters on Pb2+ separation from wastewater using electrodialysis, Desalination. 167 (2004) 379–385. https://doi.org/10.1016/j.desal.2004.06.150.

141. C.V. Gherasim, J. Křivčík, P. Mikulášek, Investigation of batch electrodialysis process for removal of lead ions from aqueous solutions, Chemical Engineering Journal. 256 (2014) 324–334. https://doi.org/10.1016/j.cej.2014.06.094.

142. A. Abou-Shady, C. Peng, J. Bi, H. Xu, J. Almeria O, Recovery of Pb (II) and removal of NO 3- from aqueous solutions using integrated electrodialysis, electrolysis, and adsorption process, Desalination. 286 (2012) 304–315. https://doi.org/10.1016/j.desal.2011.11.041.

143. M. Boucher, N. Turcotte, V. Guillemette, G. Lantagne, A. Chapotot ', G. Pourcelly ', R. Sandeaux ', C. Gavach ', Recovery of spent acid by electrodialysis in the zinc hydrometallurgy industry: performance study of different cation-exchange membranes, Hydrometallurgy. 45 (1997) 137-160. https://doi.org/10.1016/S0304-386X(96)00069-2

144. D. Abu-Ghunmi, L. Abu-Ghunmi, B. Kayal, A. Bino, Circular economy and the opportunity cost of not "closing the loop" of water industry: The case of Jordan, J Clean Prod. 131 (2016) 228–236. https://doi.org/10.1016/j.jclepro.2016.05.043.

145. P. Morseletto, C.E. Mooren, S. Munaretto, Circular Economy of Water: Definition, Strategies and Challenges, Circular Economy and Sustainability. 2 (2022) 1463–1477. https://doi.org/10.1007/s43615-022-00165-x.

146. J. Mustafa, A.H. Al-Marzouqi, M.H. El-Naas, N. Ghasem, Electrodialysis based waste utilization methodology for the desalination industry, Desalination. 520 (2021). https://doi.org/10.1016/j.desal.2021.115327.

147. J. Mustafa, A.H. Al-Marzouqi, N. Ghasem, M.H. El-Naas, B. Van der Bruggen, Electrodialysis process for carbon dioxide capture coupled with salinity reduction: A statistical and quantitative investigation, Desalination. 548 (2023). https://doi.org/10.1016/j.desal.2022.116263.

148. reigG.J. Doornbusch, M. Tedesco, J.W. Post, Z. Borneman, K. Nijmeijer, Experimental investigation of multistage electrodialysis for seawater desalination, Desalination. 464 (2019) 105–114. https://doi.org/10.1016/j.desal.2019.04.025.

149. N.C. Wright, A.G. Winter, Justification for community-scale photovoltaic-powered electrodialysis desalination systems for inland rural villages in India, Desalination. 352 (2014) 82–91. https://doi.org/10.1016/j.desal.2014.07.035.

150. G. Doornbusch, M. van der Wal, M. Tedesco, J. Post, K. Nijmeijer, Z. Borneman, Multistage electrodialysis for desalination of natural seawater, Desalination. 505 (2021). https://doi.org/10.1016/j.desal.2021.114973.

151. Q.B. Chen, Z. Tian, J. Zhao, J. Wang, P.F. Li, Y. Xu, Near-zero liquid discharge and reclamation process based on electrodialysis metathesis for high-salinity wastewater with high scaling potential, Desalination. 525 (2022). https://doi.org/10.1016/j.desal.2021.115390.

152. A.N. Vargas, J. Ladino, Economic viability analysis on seawater desalination by electrodialysis as an alternative for water potabilization in Pueblo Viejo, Colombia, Chem Eng Trans. 57 (2017) 493–498. https://doi.org/10.3303/CET1757083.

153. N.C. Wright, S.R. Shah, S.E. Amrose, A.G. Winter, A robust model of brackish water electrodialysis desalination with experimental comparison at different size scales, Desalination. 443 (2018) 27–43. https://doi.org/10.1016/j.desal.2018.04.018.

154. P.A. Sosa-Fernandez, J.W. Post, H. Bruning, F.A.M. Leermakers, H.H.M. Rijnaarts, Electrodialysis-based desalination and reuse of sea and brackish polymer-flooding produced water, Desalination. 447 (2018) 120–132. https://doi.org/10.1016/j.desal.2018.09.012.

155. J. Choi, Y. Oh, S. Chae, S. Hong, Membrane capacitive deionization-reverse electrodialysis hybrid system for improving energy efficiency of reverse osmosis seawater desalination, Desalination. 462 (2019) 19–28. https://doi.org/10.1016/j.desal.2019.04.003.

156. K. Ghyselbrecht, A. Silva, B. Van der Bruggen, K. Boussu, B. Meesschaert, L. Pinoy, Desalination feasibility study of an industrial NaCl stream by bipolar membrane electrodialysis, J Environ Manage. 140 (2014) 69–75. https://doi.org/10.1016/j.jenvman.2014.03.009.

157. A. Gonzalez-Vogel, J.J. Moltedo, O.J. Rojas, Desalination by pulsed electrodialysis reversal: Approaching fully closed-loop water systems in wood pulp mills, J Environ Manage. 298 (2021). https://doi.org/10.1016/j.jenvman.2021.113518.

158. E.S. Kim, S. Dong, Y. Liu, M.G. El-Din, Desalination of oil sands process-affected water and basal depressurization water in Fort McMurray, Alberta, Canada: Application of electrodialysis, Water Science and Technology. 68 (2013) 2668–2675. https://doi.org/10.2166/wst.2013.533.

159. N. Mir, Y. Bicer, Solar-pond assisted reverse osmosis-electrodialysis system for seawater desalination and hydroponic fertilizer solution production, Energy Sources, Part A: Recovery, Utilization and Environmental Effects. (2021). https://doi.org/10.1080/15567036.2021.2008060.

160. S. Dara, M. Lindstrom, J. English, A. Bonakdarpour, B. Wetton, D.P. Wilkinson, Conversion of saline water and dissolved carbon dioxide into value-added chemicals by

electrodialysis, Journal of CO2 Utilization. 19 (2017) 177–184. https://doi.org/10.1016/j.jcou.2017.03.013.

161. Y. xiang Jia, X. Chen, M. Wang, B. bei Wang, A win-win strategy for the reclamation of waste acid and conversion of organic acid by a modified electrodialysis, Sep Purif Technol. 171 (2016) 11–16. https://doi.org/10.1016/j.seppur.2016.07.009.

162. P.P. Sharma, S. Gahlot, A. Rajput, R. Patidar, V. Kulshrestha, Efficient and Cost Effective Way for the Conversion of Potassium Nitrate from Potassium Chloride Using Electrodialysis, ACS Sustain Chem Eng. 4 (2016) 3220–3227. https://doi.org/10.1021/acssuschemeng.6b00248.

163. L. Yu, A. Lin, L. Zhang, C. Chen, W. Jiang, Application of electrodialysis to the production of Vitamin C, Chemical Engineering Journal. 78 (2000) 153-157. https://doi.org/10.1016/S1385-8947(00)00136-4

164. A. Achoh, V. Zabolotsky, S. Melnikov, Conversion of water-organic solution of sodium naphtenates into naphtenic acids and alkali by electrodialysis with bipolar membranes, Sep Purif Technol. 212 (2019) 929–940. https://doi.org/10.1016/j.seppur.2018.12.013.

165. A. Chmielarz, W. Gnot, Conversion of zinc chloride to zinc sulphate by electrodialysis- a new concept for solving the chloride ion problem in zinc hydrometallurgy, Hydrometallurgy 61 (2001) 21-43. https://doi.org/10.1016/S0304-386X(01)00153-0

166. D. Rindfleisch, B. Syska, Z. Lazarova, K. Schtigerl, Integrated membrane extraction, enzymic conversion and electrodialysis for the synthesis of ampicillin from penicillin G, 1997.

167. M. Bailly, Production of organic acids by bipolar electrodialysis: realizations and perspectives, Desalination. 144 (2002) 57–162. https://doi.org/10.1016/S0011-9164(02)00305-3

168. M.L. Lameloise, R. Lewandowski, Recovering l-malic acid from a beverage industry waste water: Experimental study of the conversion stage using bipolar membrane electrodialysis, J Memb Sci. 403–404 (2012) 196–202. https://doi.org/10.1016/j.memsci.2012.02.053.

169. S.S. Melnikov, O.A. Mugtamov, V.I. Zabolotsky, Study of electrodialysis concentration process of inorganic acids and salts for the two-stage conversion of salts into acids utilizing bipolar electrodialysis, Seperation and Purification Technology. 235 (2020) 116198. https://doi.org/https://doi.org/10.1016/j.seppur.2019.116198.

170. H. Thang, W. Koschuh, K.D. Kulbe, S. Uromtls, C. Krotscheck, S. Novalin, Desalination of high salt content mixture by two-stage electrodialysis as the first step of separating valuable substances from grass silage, Desalination. 162 (2004) 343–353. https://doi.org/10.1016/S0011-9164(04)00068-2

171. P. Vadthya, A. Kumari, C. Sumana, S. Sridhar, Electrodialysis aided desalination of crude glycerol in the production of biodiesel from oil feed stock, Desalination. 362 (2015) 133–140. https://doi.org/10.1016/j.desal.2015.02.001.

172. B.S. Al-Anzi, A. Al-Rashidi, L. Abraham, J. Fernandes, A. Al-Sheikh, A. Alhazza, Brine management from desalination plants for salt production utilizing high current density electrodialysis-evaporator hybrid system: A case study in Kuwait, Desalination. 498 (2021). https://doi.org/10.1016/j.desal.2020.114760.

173. Y. Yang, X. Gao, A. Fan, L. Fu, C. Gao, An innovative beneficial reuse of seawater concentrate using bipolar membrane electrodialysis, J Memb Sci. 449 (2014) 119–126. https://doi.org/10.1016/j.memsci.2013.07.066.

174. C.Y. Wei, S.Y. Pan, Y.I. Lin, T.N.D. Cao, Anaerobic swine digestate valorization via energy-efficient electrodialysis for nutrient recovery and water reclamation, Water Res. 224 (2022). https://doi.org/10.1016/j.watres.2022.119066.

175. Y. Tanaka, M. Reig, S. Casas, C. Aladjem, J.L. Cortina, Computer simulation of ion-exchange membrane electrodialysis for salt concentration and reduction of RO discharged brine for salt production and marine environment conservation, Desalination. 367 (2015) 76–89. https://doi.org/10.1016/j.desal.2015.03.022.

176. Z. Wang, P. He, H. Zhang, N. Zhang, F. Lü, Desalination, nutrients recovery, or products extraction: Is electrodialysis an effective way to achieve high-value utilization of liquid digestate?, Chemical Engineering Journal. 446 (2022). https://doi.org/10.1016/j.cej.2022.136996.

177. J. Meng, L. Shi, Z. Hu, Y. Hu, P. Lens, S. Wang, X. Zhan, Novel electro-ion substitution strategy in electrodialysis for ammonium recovery from digested sludge centrate in coastal regions, J Memb Sci. 642 (2022). https://doi.org/10.1016/j.memsci.2021.120001.

178. Y. Li, Z.L. Ye, R. Yang, S. Chen, Synchronously recovering different nutrient ions from wastewater by using selective electrodialysis, Water Science and Technology. 86 (2022) 2627–2641. https://doi.org/10.2166/wst.2022.352.

179. Y. Oren, E. Korngold, N. Daltrophe, R. Messalem, Y. Volkman, L. Aronov, M. Weismann, N. Bouriakov, P. Glueckstern, J. Gilron, Pilot studies on high recovery BWRO-EDR for near zero liquid discharge approach, Desalination. 261 (2010) 321–330. https://doi.org/10.1016/j.desal.2010.06.010.

180. B. Yuzer, M.I. Aydin, H. Yildiz, B. Hasançebi, H. Selcuk, Y. Kadmi, Optimal performance of electrodialysis process for the recovery of acid wastes in wastewater: Practicing circular economy in aluminum finishing industry, Chemical Engineering Journal. 434 (2022). https://doi.org/10.1016/j.cej.2022.134755.

181. M.T. Ali, H.E.S. Fath, P.R. Armstrong, A comprehensive techno-economical review of indirect solar desalination, Renewable and Sustainable Energy Reviews. 15 (2011) 4187–4199. https://doi.org/10.1016/j.rser.2011.05.012.

182. A. A., L.L. Kazmerski, Renewable Energy Opportunities in Water Desalination, Desalination, Trends and Technologies. (2011). https://doi.org/10.5772/14779

183. M. Schorr, Desalination, Trends and Technologies, (2011). https://doi.org/10.5772/583

184. J.M. Ortiz, E. Expósito, F. Gallud, V. García-García, V. Montiel, V.A. Aldaz, Desalination of underground brackish waters using an electrodialysis system powered directly by photovoltaic energy, Solar Energy Materials and Solar Cells. 92 (2008) 1677–1688. https://doi.org/10.1016/j.solmat.2008.07.020.

185. N. Mir, Y. Bicer, Integration of electrodialysis with renewable energy sources for sustainable freshwater production: A review, Journal of Environmental Management. 289 (2021) 112496. https://doi.org/10.1016/j.jenvman.2021.112496.

186. J. Uche, F. Círez, A.A. Bayod, A. Martínez, On-grid and off-grid batch-ED (electrodialysis) process: Simulation and experimental tests, Energy. 57 (2013) 44–54. https://doi.org/10.1016/j.energy.2013.02.056.

187. Y. Liu, X. Wu, X. Wu, L. Dai, J. Ding, X. Ye, R. Chen, R. Ding, J. Liu, Y. Jin, B. Van Der Bruggen, Recovery of nickel , phosphorus and nitrogen from electroless nickel-plating wastewater using bipolar membrane electrodialysis, Journal of Cleaner Production. 382 (2023) 135326. https://doi.org/10.1016/j.jclepro.2022.135326.

188. J. Kim, S. Yoon, M. Choi, K.J. Min, K.Y. Park, K. Chon, S. Bae, Metal ion recovery from electrodialysis-concentrated plating wastewater via pilot-scale sequential electrowinning/chemical precipitation, Journal of Cleaner Production. 330 (2022) 129879. https://doi.org/10.1016/j.jclepro.2021.129879.

189. A. Campione, A. Cipollina, F. Calise, A. Tamburini, M. Galluzzo, G. Micale, Coupling electrodialysis desalination with photovoltaic and wind energy systems for energy storage: Dynamic simulations and control strategy, Energy Conversion and Management. 216 (2020) 112940. https://doi.org/10.1016/j.enconman.2020.112940.

190. X. Sun, H. Lu, J. Wang, Recovery of citric acid from fermented liquid by bipolar membrane electrodialysis, Journal of Cleaner Production. 143 (2017) 250–256. https://doi.org/10.1016/j.jclepro.2016.12.118.

191. A. Gonzalez, M. Grágeda, S. Ushak, Assessment of pilot-scale water purification module with electrodialysis technology and solar energy, Applied Energy. 206 (2017) 1643–1652. https://doi.org/10.1016/j.apenergy.2017.09.101.

192. W. He, S. Amrose, N.C. Wright, T. Buonassisi, I.M. Peters, A.G. Winter, Field demonstration of a cost-optimized solar powered electrodialysis reversal desalination system in rural India, Desalination. 476 (2020) 114217. https://doi.org/10.1016/j.desal.2019.114217.

193. N.C. Wright, I.M. Peters, S. Amrose, A.G. Winter, Preliminary Field Test Results From a Photovoltaic, (2018) 1–7.

194. H.M.N. AlMadani, Water desalination by solar powered electrodialysis process, Renewable Energy. 28 (2003) 1915–1924. https://doi.org/10.1016/S0960-1481(03)00014-4.

195. S. Hidayat, Y.H. Song, J.Y. Park, A comparison of mono- and multi-valent ions as stack feed solutions in microbial reverse-electrodialysis electrolysis cells and their effects on hydrogen generation, Int Biodeterior Biodegradation. 113 (2016) 28–33. https://doi.org/10.1016/j.ibiod.2016.03.008.

196. T. Scarazzato, Z. Panossian, J.A.S. Tenório, V. Pérez-Herranz, D.C.R. Espinosa, A review of cleaner production in electroplating industries using electrodialysis, J Clean Prod. 168 (2017) 1590–1602. https://doi.org/10.1016/j.jclepro.2017.03.152

197. M. Greiter, S. Novalin, M. Wendland, K.D. Kulbe, J. Fischer, Electrodialysis versus ion exchange: Comparison of the cumulative energy demand by means of two applications, J Memb Sci. 233 (2004) 11–19. https://doi.org/10.1016/j.memsci.2003.11.027.

198. J. Liu, J. Liang, X. Feng, W. Cui, H. Deng, Z. Ji, Y. Zhao, X. Guo, J. Yuan, Effects of inorganic ions on the transfer of weak organic acids and their salts in electrodialysis process, J. Membr. Sci. 624 (2021), 119109, https://doi.org/10.1016/j.memsci.2021.119109.

199. W.-F. Wen, J. Wang, C.-Y. Zhong, Q. Chen, W.-M. Zhang, Direct production of lithium nitrate from the primary lithium salt by electrodialysis metathesis, J. Membr. Sci. 654 (2022), 120555, https://doi.org/10.1016/j.memsci.2022.120555

200. L. Shi, Z. Hu, W.S. Simplicio, S. Qiu, L. Xiao, B. Harhen, X. Zhan, Antibiotics in nutrient recovery from pig manure via electrodialysis reversal: sorption and migration associated with membrane fouling, J. Membr. Sci. 597 (2020), 117633, https://doi.org/10.1016/j.memsci.2019.117633

201. X. Duan, C. Wang, T. Wang, X. Xie, X. Zhou, Y. Ye, A polysulfone-based anion exchange membrane for phosphoric acid concentration and purification by electro-electrodialysis, J. Membr. Sci. 552 (2018), 86–94, https://doi.org/10.1016/j.memsci.2018.02.004

202. A. Lejarazu-Larranaga, S. Molina, J.M. Ortiz, R. Navarro, E. Garcia-Calvo, Circular economy in membrane technology: using end-of-life reverse osmosis modules for preparation of recycled anion exchange membranes and validation in electrodialysis, J. Membr. Sci. 593(2020), 117423, https://doi.org/10.1016/j.memsci.2019.117423

203. T. Leon, J. Lopez, R. Torres, J. Grau, L. Jofre, J.-L. Cortina, Describing ion transport and water splitting in an electrodialysis stack with bipolar membranes by a 2-D model: experimental validation, J. Membr. Sci. 660 (2022), 120835, https://doi.org/10.1016/j.memsci.2022.120835

204. M. Szczygiełda, K. Prochaska, Alpha-ketoglutaric acid production using electrodialysis with bipolar membrane, J. Membr. Sci. 536 (2017), 37–43. https://doi.org/10.1016/j.memsci.2017.04.059

205. S. Al-Amshawee, M.Y.B.M. Yunus, A.A.M. Azoddein, D.G. Hassell, I.H. Dakhil, H.A. Hasan, Electrodialysis desalination for water and wastewater: a review, Chem. Eng. J. 380 (2020), 122231, https://doi.org/10.1016/j.cej.2019.122231

206. V. Yadav, N.H. Rathod, J. Sharma, V. Kulshrestha, Long side-chain type partially cross-linked poly (vinylidene fluoride-co-hexafluoropropylene) anion exchange membranes for desalination via electrodialysis, J. Membr. Sci. 622 (2021), 119034, https://doi.org/10.1016/j.memsci.2020.119034

207. M.M. Generous, N.A.A. Qasem, U.A. Akbar, S.M. Zubair, Techno-economic assessment of electrodialysis and reverse osmosis desalination plants, Sep. Purif. Technol. 272 (2021), 118875. https://doi.org/10.1016/j.seppur.2021.118875

208. Y. Zhang, K. Ghyselbrecht, R. Vanherpe, B. Meesschaert, L. Pinoy, B. Van Der Bruggen, RO concentrate minimization by electrodialysis: techno-economic analysis and environmental concerns, J. Environ. Manage. 107 (2012), 28–36, https://doi.org/10.1016/j.jenvman.2012.04.020

209. A. A. Moya, Uphill transport in improved reverse electrodialysis by removal of divalent cations in the dilute solution: a Nernst-Planck based study, J. Membr. Sci. 598 (2020), 117784, https://doi.org/10.1016/j.memsci.2019.117784

210. Y.D. Ahdab, D. Rehman, J.H. Lienhard, Corrigendum to "brackish water desalination for greenhouses: improving groundwater quality for irrigation using monovalent selective electrodialysis reversal, J. Membr. Sci. 610 (2021), 118072, https://doi.org/10.1016/j.memsci.2020.118906

211. J. Jang, Y. Kang, K. Kim, S. Kim, M. Son, S.-S. Chee, I.S. Kim, Concrete-structured Nafion@MXene/cellulose acetate cation exchange membrane for reverse electrodialysis, J. Membr. Sci. 646 (2022), 120239, https://doi.org/10.1016/j.memsci.2021.120239

212. P. Song, M. Wang, B. Zhang, Y. Jia, Y. Chen, Fabrication of proton permselective composite membrane for electrodialysis-based waste acid reclamation, J. Membr. Sci. 592 (2019), 117366. https://doi.org/10.1016/j.memsci.2019.117366

213. E. Mercer, C.J. Davey, D. Azzini, A.L. Eusebi, R. Tierney, L. Williams, Y. Jiang, A. Parker, A. Kolios, S. Tyrrel, E. Cartmell, M. Pidou, E.J. McAdam, Hybrid membrane distillation reverse electrodialysis configuration for water and energy recovery from human urine: an opportunity for off-grid decentralised sanitation, J. Membr. Sci. 584 (2019), 343–352. https://doi.org/10.1016/j.memsci.2019.05.010

214. H. Kim, D. Kim, H. Seo, H.-Y. Park, J. Choi, H. Kim, J. Yoo, Y.-W. Choi, H. Yang, S.-C. Jeon, Y.-G. Jung, S. Yang, Facile fabrication of carbon nanotube embedded pore filling

ion exchange membrane with high ion exchange capacity and permselectivity for high-performance reverse electrodialysis, J. Membr. Sci. 654 (2022), 120568, https://doi.org/10.1016/j.memsci.2022.120568

215. Wang, Y., Zhang, X., Xu, T., Integration of conventional electrodialysis and electrodialysis with bipolar membranes for production of organic acids. J. Membr. Sci. 365 (2010), 294–301, https://doi.org/10.1016/j.memsci.2010.09.018

216. R.S. Kingsbury, K. Chu, O. Coronell, Energy storage by reversible electrodialysis: the concentration battery, J. Membr. Sci. 495 (2015), 502–516, https://doi.org/10.1016/j.memsci.2015.06.050

217. A.M. Elgarahy, M.G. Eloffy, A. Hammad, A.N. Saber, D.M. El-Sherif, A. Mohsen, M. Abouzid, K.Z. Elwakeel, Hydrogen production from wastewater, storage, economy, governance and applications: a review, Environ. Chem. Lett. 20 (2022), 3453–3504, https://doi.org/10.1007/s10311-022-01480-3.

218. J., Shen, J., Huang, H., Ruan, J., Wang, B., Van Der Bruggen, Techno-economic analysis of resource recovery of glyphosate liquor by membrane technology, Desalination 342(2014), 118–125, https://doi.org/10.1016/j.desal.2013.11.041

219. C. Fernandez-Gonzalez, A. Dominguez-Ramos, R. Ibanez, A. Irabien, Sustainability assessment of electrodialysis powered by photovoltaic solar energy for freshwater production, Renew. Sustain. Energy Rev. 47 (2015), 604–615, https://doi.org/10.1016/j.rser.2015.03.018

220. I. Wu, R.J. Park, R. Ghosh, M.-C. Kuo, S. Seifert, E.B. Coughlin, A.M. Herring, Enhancing desalination performance by manipulating block ratios in a polyethylene-based triblock copolymer anion exchange membrane for electrodialysis, J. Membr. Sci. 647 (2022), 120295, https://doi.org/10.1016/j.memsci.2022.120295

221. M.C. Marti-Calatayud, E. Evdochenko, J. Bar, M. Garcia-Gabaldon, M. Wessling, V. Perez-Herranz, Tracking homogeneous reactions during electrodialysis of organic acids via EIS, J. Membr. Sci. 595(2020), 117592, https://doi.org/10.1016/j.memsci.2019.117592

222. J. Zhao, L. Ren, Q. Chen, P. Li, J. Wang, Fabrication of cation exchange membrane with excellent stabilities for electrodialysis: a study of effective sulfonation degree in ion transport mechanism, J. Membr. Sci. 615 (2020), 118539, https://doi.org/10.1016/j.memsci.2020.118539

223. A. Campione, L. Gurreri, M. Ciofalo, G. Micale, A. Tamburini, A. Cipollina, (2018) Electrodialysis for water desalination: a critical assessment of recent developments on process fundamentals, models and applications, Desalination, 434 (2018), 121-160. https://doi.org/10.1016/j.desal.2017.12.044.

224. M. Demircioglu, N. Kabay, E. Ersoz, I. Kurucaovali, C. Şafak, N. Gizli, Cost comparison and efficiency modeling in the electrodialysis of brine, Desalination 136 (2001), 317–323, https://doi.org/10.1016/S0011-9164(01)00194-1

225. A.H. Avci, T. Rijnaarts, E. Fontananova, G. Di Profio, I.F.V. Vankelecom, W.M. De Vos, E. Curcio, Sulfonated polyethersulfone based cation exchange membranes for reverse electrodialysis under high salinity gradients, J. Membr. Sci. 595 (2020), 117585, https://doi.org/10.1016/j.memsci.2019.117585

226. Y. Luo, Y. Liu, J. Shen, B. Van der Bruggen, Application of bipolar membrane electrodialysis in environmental protection and resource recovery: a review, Membranes, 12 (2022), 829, https://doi.org/10.3390/membranes12090829

227. L. Liu, Q. Cheng, Mass transfer characteristic research on electrodialysis for desalination and regeneration of solution: a comprehensive review. Renew. Sustain. Energy Rev. 134(2020), 110115, https://doi.org/10.1016/j.rser.2020.110115

228. S.K.A. Al-Amshawee, M.Y.B. Mohd Yunus, Impact of membrane spacers on concentration polarization, flow profile, and fouling at ion exchange membranes of electrodialysis desalination: diagonal net spacer vs. ladder-type configuration, Chem. Eng. Res. Des. 191(2023), 197–213, https://doi.org/10.1016/j.cherd.2023.01.012

229. H. Fan, Y. Huang, N.Y. Yip, Advancing the conductivity-permselectivity trade-off of electrodialysis ion-exchange membranes with sulfonated CNT nanocomposites, J. Membr. Sci. 610 (2020), 118259, https://doi.org/10.1016/j.memsci.2020.118259

230. B. Wang, Z. Li, Q. Lang, M. Tan, C. Ratanatamskul, M. Lee, Y. Liu, Y. Zhang, A comprehensive investigation on the components in ionic liquid-based polymer inclusion membrane for Cr(VI) transport during electrodialysis, J. Membr. Sci. 604 (2020), 118016, https://doi.org/10.1016/j.memsci.2020.118016

231. A. Merkel, A.M. Ashrafi, J. Ecer, Bipolar membrane electrodialysis assisted pH correction of milk whey, J. Membr. Sci. 555 (2018), 185–196, https://doi.org/10.1016/j.memsci.2018.03.035

232. E.H. Rotta, L., Marder, V. Perez-Herranz, A.M. Bernardes, Characterization of an anion-exchange membrane subjected to phosphate and sulfate separation by electrodialysis at overlimiting current density condition. J. Membr. Sci. 635 (2021), 119510, https://doi.org/10.1016/j.memsci.2021.119510

233. T. Rottiers, G. De La Marche, B. Van Der Bruggen, L. Pinoy, Co-ion fluxes of simple inorganic ions in electrodialysis metathesis and conventional electrodialysis, J. Membr. Sci. 492 (2015), 263–270, https://doi.org/10.1016/j.memsci.2015.05.066

234. H. Yan, K. Peng, J. Yan, C. Jiang, Y. Wang, H. Feng, Z. Yang, L. Wu, T. Xu, Bipolar membrane-assisted reverse electrodialysis for high power density energy conversion via acid-

base neutralization, J. Membr. Sci. 647 (2022), 120288, https://doi.org/10.1016/j.memsci.2022.120288

235. M.A.S. Rodrigues, F.D.R. Amado, J.L.N. Xavier, K.F. Streit, A.M. Bernardes, J.Z. Ferreira, Application of photoelectrochemical-electrodialysis treatment for the recovery and reuse of water from tannery effluents, Journal of Cleaner Production. 16 (2008) 605–611. https://doi.org/10.1016/j.jclepro.2007.02.002.

236. E. Oztekin, S. Altin, WASTEWATER TREATMENT BY ELECTRODIALYSIS SYSTEM AND FOULING PROBLEMS, TOJSAT. 6 (2016) 91–99. www.tojsat.net.

237. T. Chen, J. Bi, Z. Ji, J. Yuan, Y. Zhao, Application of bipolar membrane electrodialysis for simultaneous recovery of high-value acid / alkali from saline wastewater : An in-depth review, Water Research. 226 (2022) 119274. https://doi.org/10.1016/j.watres.2022.119274.

238. X. Liu, M. He, D. Calvani, H. Qi, K.B.S.S. Gupta, H.J. de Groot, G.A. Sevink, F. Buda, U. Kaiser, G.F. Schneider, Power generation by reverse electrodialysis in a single-layer nanoporous membrane made from core–rim polycyclic aromatic hydrocarbons, Nat. Nanotechnol., 15 (2020), 307-312, https://doi.org/10.1038/s41565-020-0641-5

239. N. White, M. Misovich, E. Alemayehu, A. Yaroshchuk, M.L. Bruening, Highly selective separations of multivalent and monovalent cations in electrodialysis through Nafion membranes coated with polyelectrolyte multilayers, Polymer (Guildf). 103 (2016) 478–485. https://doi.org/10.1016/j.polymer.2015.12.019.

240. Zoungrana, A., & Çakmakci, M. (2021). From non-renewable energy to renewable by harvesting salinity gradient power by reverse electrodialysis: A review. In International Journal of Energy Research (Vol. 45, Issue 3, pp. 3495–3522). John Wiley and Sons Ltd. https://doi.org/10.1002/er.6062