Application of Bipolar Membrane Electrodialysis in Environmental Protection and Resource Recovery: A Review

Yu Luo 1, Yaoxing Liu 1,2,*, Jiangnan Shen 3,* and Bart Van der Bruggen 2,4

1 College of Environmental and Resource Sciences, College of Carbon Neutral Modern Industry, Fujian Key Laboratory of Pollution Control & Resource Reuse, Fujian Normal University, Fuzhou 350007, China
2 Department of Chemical Engineering, ProESS-Process Engineering for Sustainable System, KU Leuven, Celestijnenlaan 200F, B-3001 Leuven, Belgium
3 College of Chemical Engineering, Zhejiang University of Technology, Hangzhou 310014, China
4 Faculty of Engineering and the Built Environment, Tshwane University of Technology, Private Bag X680, Pretoria 0001, South Africa

* Correspondence: yxl19830218@fjnu.edu.cn (Y.L.); shenjn@zjut.edu.cn (J.S.)

Abstract: Bipolar membrane electrodialysis (BMED) is a new membrane separation technology composed of electrodialysis (ED) through a bipolar membrane (BPM). Under the action of an electric field, H2O can be dissociated to H+ and OH−, and the anions and cations in the solution can be recovered as acids and bases, respectively, without adding chemical reagents, which reduces the application cost and carbon footprint, and leads to simple operation and high efficiency. Its application is becoming more widespread and promising, and it has become a research hotspot. This review mainly introduces the application of BMED to recovering salts in the form of acids and bases, CO2 capture, ammonia nitrogen recovery, and ion removal and recovery from wastewater. Finally, BMED is summarized, and future prospects are discussed.

Keywords: bipolar membrane electrodialysis; acid and base; carbon dioxide; ammonia nitrogen; wastewater

1. Introduction

Electrodialysis (ED) is a membrane separation technology, and the ion exchange membrane present in ED is divided into anion-exchange membrane (AEM) and cation-exchange membrane (CEM). CEM and AEM are selective for cation and anion transfer [1–3] under an electric field [4–6]. ED is widely used in (bio)chemistry, food processing, wastewater treatment, chemical recycling, and the removal of toxic components, but the high energy consumption limits its wider development [7].

In 1956, Frilette [8] made a breakthrough in membrane separation technology. He was the first to propose a bipolar membrane (BPM) [9], which is a special ion exchange membrane that consists of an AEM and a CEM [10]. Their combined thickness is less than 10 nm [11,12]. Under the reverse bias of a DC electric field, H+ and OH− can be generated by dissociating H2O [13]. BPM is used in the (bio)chemical industry, as well as for food processing, environmental protection, and energy conversion and storage, because it can acidify organic salts in situ without causing salt contamination, and converts the cations into a base (which can be reused to produce organic salts) [14].

Over the past 20 years, bipolar membrane electrodialysis (BMED), a system combining ED and BPM, has been developed for its ability to convert anions and cations into acids and bases, respectively. BMED is composed of BPM, CEM, and AEM in a certain arrangement [15] and has three basic membrane structures (three-chamber BMED; two-chamber BMED containing acids or base) depending on the application. Among them, the three-chamber BMED (Figure 1a) contains CEM, AEM, and BPM in each membrane repeating unit, and the benefit of it is that the salts can be separated and recovered as acids...
and bases [13]. Two-chamber BMED includes base-BMED (Figure 1b) and acid-BMED (Figure 1c); the difference from the three-chamber BMED is that an AEM or CEM is removed from each membrane repeating unit, resulting in only base or acid being produced. Base-BMED (Figure 1b) can be used to treat weak acid salts (organic acid salts) for obtaining a relatively pure base; acid-BMED (Figure 1c) can be used to convert weak base salts into a relatively pure acid. Moreover, two-chamber BMED has advantages, such as requiring a smaller membrane area (per repeating unit), simple operation, high efficiency, low energy consumption, and only with two outlet streams [13]. However, the base generated by the cathode in the two-chamber BMED is easily transported to an acid chamber through the AEM, neutralizing the acid, therefore reducing the amount of acid and current efficiency [16].

Figure 1. Schematic diagram of BMED: (a) three-chamber BMED; (b) two-chamber: base-BMED; and (c) two-chamber: acid-BMED [17].
In a three-chamber BMED, the basic units are repeatedly placed between the electrodes. The salt solution flows in the chamber between the AEM and the CEM; the CEM is not directly in contact with the acid, and the AEM is not directly in contact with the base, so the durability of the membrane is significantly increased compared to in the two-chamber BMED [18]. This also overcomes the disadvantage of ion leakage that was present in the two-chamber BMED. When a direct current is applied, water will dissociate into equal amounts of $H^+$ and $OH^-$ in the BPM; the generated $H^+$ forms $HX$ with the $X^-$ ions provided by the salt solution, $OH^-$ and $M^+$ ions provided by the salt solution form MOH, and the corresponding acids and base are obtained. It was shown that concentrations of acids and base as high as 6 M can be produced in a three-chamber BMED. However, its energy consumption is relatively high due to the resistance of the salt solution increasing with the ion migration, which resulted in a high voltage under the condition of a stable current density.

Compared with other electrochemical technologies, BMED has the characteristics of lower energy consumption and higher economic efficiency. The water dissociation potential (0.828 V) required in BPM is much lower than that of water electrolysis on electrodes (2.057 V). The electrolysis reaction is compared as follows (assuming that 1 mol of acid and base are both generated) [19]:

The overall electrolysis reaction on an electrode:

$$3H_2O \rightarrow 1/2O_2 + H_2 + 2H^+ + 2OH^-, \text{ theoretical potential } 2.057 \text{ V}$$  \(1\)

cathodic reaction:

$$2H_2O + 2e \rightarrow H_2 + 2OH^-, \text{ theoretical potential } 0.828 \text{ V}$$  \(2\)
anodic reaction:

$$H_2O \rightarrow 1/2O_2 + 2H^+ + 2e, \text{ theoretical potential } 1.229 \text{ V}$$  \(3\)

Bipolar membrane water dissociation reaction:

$$2H_2O \xrightleftharpoons[k_{-1}]{k_1} H_3O^+ + 2OH^-, \text{ theoretical potential } 0.828 \text{ V}$$  \(4\)

where $k_1$ is the water dissociation rate constant, and $k_{-1}$ is the water recombination rate constant.

The water dissociation reaction in BPM is described as a two-stage protonation–deprotonation reaction [20]. The protonation–deprotonation mechanism suggests the possibility of generating $H^+$ and $OH^-$ ions via proton transfer reactions between water and immobilized charged groups [21–23], involving the participation of catalysts in the dissociation of water, and it is believed that the water dissociation reaction depends on the catalytic activity of the immobilized group. Therefore, the reaction in Equation (4) can be divided into the following processes:

$$B + H_2O \xrightleftharpoons[k_{-1}]{k_1} BH^+ + OH^-$$  \(5\)

$$BH^+ + H_2O \xrightleftharpoons[k_{-2}]{k_3} B + H_3O^+,$$  \(6\)
where B is a weak base, BH$^+$ is the catalytic center (i.e., fixed charged groups of AEM), $k_{1,2}$ is the forward rate constant, and $k_{-1,-2}$ the backward rate constant.

$$AH + H_2O \xrightleftharpoons{k_1}{k_{-1}} A^- + H_3O^- \tag{7}$$

$$A^- + H_2O \xrightleftharpoons{k_2}{k_{-2}} AH + OH^- \tag{8}$$

where $A^-$ is the catalytic center in the membrane.

If the dissociated ions combine with the ions in solution, the overall reaction of BPM can also be written as:

$$MX + H_2O \rightarrow MOH + HX \tag{9}$$

where MX refers to a generic electrolyte and MOH and HX to its corresponding base and acid, respectively.

The energy consumption of electrohydrolysis for 1 mol of water is 198.5 KJ/mol on electrodes, and 79.9 KJ/mol in BPM. H$_2$ and O$_2$ are not generated during the BMED process, which has no effect on the electrode. This gives BMED better application prospects compared to other electrochemical technologies.

This review mainly introduces the application of BMED in terms of recovering salts in the form of acids and bases, CO$_2$ capture, ammonia nitrogen production and recovery, and ion removal and recovery from wastewater.

2. Recovering Salts in the Form of Acids and Bases

2.1. Inorganic Acid and Base Recovery from Salt Solutions

BMED technology is often used to treat high-salt wastewater. A large number of previous studies reported acid and base recovery from NaCl and Na$_2$SO$_4$ containing wastewater. For example, Gao et al. [24] used a BMED system to recover acid and base from NaCl wastewater generated from the process of generating HZSM-5 zeolite. Yang et al. [18] used a BMED to treat seawater reverse osmosis (RO) concentrate; 1 mol/L of mixed acid and base was continuously produced at a constant current density of 57 mA/cm$^2$, and the produced acid was used for pH adjustment of RO process and controlling of RO membrane fouling. In addition, the combination of BMED with other technologies is also used to treat waste acid, waste base, and other solutions. Zhuang et al. [25] recovered acid and aluminum in the form of Al(OH)$_3$ from a waste acid generated from the aluminum foil industry using a combined BMED with diffusion dialysis. When a RO-ED-BMED combination process was used to treat brine (Na$_2$SO$_4$), NaOH and H$_2$SO$_4$ were recovered and pure water was generated [26]. Reig et al. [27] integrated an ED + BMED system to treat high-salt wastewater. ED was used to concentrate salts and BMED was used to convert salts to acids and bases, and 1.9 mol/L of NaOH and 2.0 mol/L of HCl were finally recovered with consumption of 1.7 kW·h/kg [28]. Badruzzaman et al. [29] proposed a new integrated membrane system (IMS)–BMED technology for treating RO high-salt wastewater, and it was found that the IMS–BMED system had certain advantages in terms of investment costs and operating costs. Chen et al. [30] first proposed a new process called BPM selective eletrodiagnosis (BMSED) to treat concentrated saline, which works by combining selective electrodialysis (SED) and BMED processes (Figure 2). The results show that the selective permeability of Na$^+$/Ca$^{2+}$ and Cl$^-$/SO$_4^{2-}$ are 5 to 10 and 50 to 60, respectively; the concentrations of NaOH and HCl increased to 2.2 and 1.9 mol/L, respectively, and the purity of NaOH and HCl were both close to 99.99%. Chen et al. [31] proposed a novel innovative hybrid selective ED (HSED) and a selective BMED (SBMED) (Figure 3) to treat seawater brine. The HSED process was used to enrich major divalent cations and anions and the SBMED process was used to produce acids and bases without any purification pretreatment. When the combination technology of ozonation and BMED
was used to treat textile wastewater, 90% of color, 37% of chemical oxygen demand, and more than 90% of salt could be removed [32].

![Figure 2. Schematic diagram of the BMSED process [30].](image)

![Figure 3. Structural diagram of SED and HSED stacks [31].](image)

Gonzalez et al. [33] determined and analyzed the scope and feasibility of BMED for recovering high-purity LiOH from an LiCl solution. The results showed that when the initial LiCl concentrations were 0.5 wt. % and 14 wt. %, the concentrations of obtained LiOH solutions were 3.34 wt. % (purity 96.0%) and 4.35 wt. % (purity 95.4%), respectively. However, when the concentration of LiCl was in the range of 25–34 wt. %, Cl\(^-\) is easily diffused into the LiOH solution; also, the phenomenon of OH\(^-\) leakage occurred with LiOH concentration increase. Currently, this can be addressed by asymmetric BPM, or by avoiding high HCl concentrations and current density. In a previous study by Kishida et al. [34], BMED was used to generate NaOH and \(\text{H}_2\text{SO}_4\). The NaOH was used in the Bayer refinery and \(\text{H}_2\text{SO}_4\) was used to neutralize bauxite residues. In their study, the purpose of treating waste with waste was realized and the main treatment process was as shown in Figure 4.
was also used by Shen et al. [44] to treat glyphosate wastewater, and glyphosate and high- 
preparation acid–base concentrations were all less than 1 mol/L. A three-chamber BMED 
produced high-purity (Cl\(^-\)) with low yield, and high energy consumption. In the study by Yao et al. [36], 86.8% of 
choline chloride was converted to choline hydroxide in a BMED system with low energy 
consumption (0.74 kWh kg\(^{-1}\)) and high current efficiency (84.6%) [37,38]. Shen et al. [39] 
produced high-purity (Cl\(^-\)/Br\(^-\) content < 500 ppm) quaternary ammonium hydroxides 
(Figure 5) in a novel four-chamber BMED; the details of the BMED are shown in Figure 4. 
Compared with traditional quaternary ammonium hydroxide synthesis methods, such 
as quaternary ammonium chloride reaction, ion exchange, and electrodialysis, there is no 
secondary pollution created in the BMED process.

In addition, BMED was used to treat some pollutants that are difficult to treat with 
traditional methods. Glyphosate (N-phosphonomethyl glycine) is a postemergent nonselective 
broad-spectrum herbicide used worldwide [40]. The glycine–dimethylphosphite and 
iminodiacetic acid processes are the two main methods for synthesizing glyphosate [41]. 
However, both methods produce large amounts of glyphosate and high-salinity liquid [42], 
the discharge of which without treatment will not only cause environmental pollution, 
but also a waste of resources [43]. In 2012, BMED was first used to treat a high-salt 
glyphosate solution [43] and the obtained acid-based solution could be used for producing 
glyphosate (Figure 6); however, the process remained at the laboratory stage, and the 
prepared acid–base concentrations were all less than 1 mol/L. A three-chamber BMED 
was also used by Shen et al. [44] to treat glyphosate wastewater, and glyphosate and high-
concentration base/acid were recovered; the current efficiency of producing NaOH with 
a concentration of 2.0 mol L\(^{-1}\) was above 67% and the corresponding energy consumption 
was 2.97 kWh kg\(^{-1}\), when the current density was 60 mAm\(^{-2}\). When the current 
density was 30 mAm\(^{-2}\), the current efficiency increased and the energy consumption 
decreased (87.13% and 2.37 kWh kg\(^{-1}\), respectively). Compared to normal methods for 
treating glyphosate wastewater, BMED avoided the high energy consumption and low 
recovery of the evaporation method, and the high-salt residue of nanofiltration [45]. BMED
was also used to treat pesticide wastewater [46], in which 99% of Na\textsubscript{2}SO\textsubscript{4} was removed and 97% of 2,6-Difluorobenzamide was recovered.
From the above, we see that BMED has wide applications in treating different salt-containing wastewaters; however, high-salt wastewater is complex and contains various inorganic ions, organic substances, and heavy metals. Among them, hardness ions and heavy metal ions can be deposited on the surface of membranes, blocking the membrane channels and reducing the effective area of the membrane; too much organic matter will cause BPM swelling or adsorption by membranes, resulting in a decrease in selectivity [47]. Therefore, BMED influent generally requires low-concentration hardness ions (such as calcium and magnesium below 0.1 mg/L) and turbidity (below 1 mg/L) to protect its membrane components. In the future application of BMED, how to pretreat wastewater and develop a fouling-resistant membrane are ongoing topics of research.

2.2. Organic Acid–Base Recovery from Salt Solution

The BMED process is also used for the production and recovery of organic acids. Normally, organic acids are produced by chemical synthesis or fermentation [48]. The products generated by chemical synthesis are usually highly pure and concentrated [49,50], but the energy consumption is high, an expensive catalyst is needed [51], and some toxic and environmentally harmful reagents are used [52,53]; these limit the development of synthetic methods. The organic acids generated by fermentation are of high purity [54], but impurities such as sugar and mineral salts [55] often exist in the fermentation broth. To obtain a high-purity product, the impurities need to be removed using separation and purification technologies including precipitation [56], acidification, extraction [57–59], crystallization, distillation, and adsorption [60]; this consumes a large amount of chemical reagents and generates a large amount of waste liquid and residues that pollute the environment. Both of these methods fail to meet the requirements of modern chemistry, characterized by “design for the environment” and “green chemistry” [61]. To avoid the above disadvantages, ED [62] and ion exchange [63] are also used to produce organic acids. ED uses the principle of the selective permeability of AEM and CEM under the action of an electric field to produce organic acids from organic acid salt solutions. Since the ED system cannot generate H\(^+\), a large amount of acid needs to be added during the ED process, which leads to high costs. The main principle of ion exchange is to exchange ions through an ion exchange resin and convert them into organic acids, but the disadvantage is that the ion exchange resin is bulky and needs to be regenerated, resulting in a large amount of acid and alkali being consumed. In recent years, BMED has often been used to produce organic acids such as citric acid, fumaric acid, vitamin C, alpha-ketoglutaric acid, salicylic acid, succinic acid, amino acids, and itaconic acid (IA) from a fermentation broth owing to its characteristics of simple operation, no addition of chemical reagents, and environmental friendliness [64]. Organic acids and bases can be generated directly by BMED through combining the H\(^+\) and OH\(^-\) generated by BMP and anions and cations in the fermentation broth. Table 1 shows the properties of ED, ion exchange, and BMED for obtaining organic acid from a fermentation broth.

| Type            | ED                     | Ion Exchange                      | BMED                                       |
|-----------------|------------------------|-----------------------------------|--------------------------------------------|
| additive        | consume a lot of acid   | consume a lot of acid and base     | does not consume any acid and base         |
| product         | produce a lot of salt waste liquid, the produced high-soda ash solution can be recycled | produces a lot of acid and base waste liquid, and it is difficult to recover | no waste liquid is produced, and the produced high-soda ash solution can be recycled |
| production scale | capable of mass production | not suitable for mass production | capable of mass production of inorganic acids and bases; the market for organic acids and bases is expanding |
| recycling effect | high recovery and high purity | the recovery efficiency is low; the purity is high | high recovery efficiency and purity         |
In the study by Xu et al. [65,66], a two-chamber BMED was used to produce citric acid from sodium citrate solution. The effect of battery configuration and salty concentration on the energy consumption and electroacidification parameters were investigated; finally, citric acid with a concentration of 30 g/L was obtained. Cauwenberg et al. [67] also successfully recovered citric acid (concentration: 8.2–20.7 wt. %) from a sodium citrate solution (initial concentration: 15–18 wt. %) using a two-chamber EDBM with current density 40–100 mA cm\(^{-2}\). Sun et al. [68] produced citric acid from a fermentation broth using a two-chamber BMED. The effect of current density, initial sodium citrate concentration, and the structure of the acid and base chambers on BMED performance were investigated, and acid recovery of 97.1% was achieved under the conditions of initial sodium citrate 3.3 wt. % and current density 40 mA cm\(^{-1}\). Yu et al. [69] applied EDBM to the acidification process of sodium L-ascorbate and sodium 2-keto-L-guluronate, replacing the original sulfation process and ion exchange method in the production of vitamin C. The conversion rate was higher than 98% with an average current efficiency of about 70% and an electricity consumption of 1 kWh/kg of vitamin C. Szczygielda et al. [70] produced \(\alpha\)-ketoglutarate from a simulated solution using a two-chamber EDBM stack. Under the optimal conditions, the obtained alpha-ketoglutaric acid concentration, current efficiency, and energy consumption were 4.83 g/L, 71.8%, and 3.72-kW h/kg, respectively. Jiang et al. [71] produced morpholine (Mp) from a sulfate Mp solution with an energy consumption of 4.27 kW h/kg.

Three-chamber BMED is also used to produce strong and weak organic acids from different solutions. A normal three-chamber BMED consists of a fermentation broth, base, and acid chamber, as shown in Figure 7 [72]. Fu et al. [73] employed different BMED to recover succinic acid from a sodium succinate solution. The properties of BMED with three different structures were investigated according to energy consumption, current efficiency, voltage drop across the stack, and yield concentration (Figure 8). It was found that the BMED could not work at a high current density and had a relatively high energy consumption. BPM-CEM-BPM BMED has a low energy consumption and high acid concentration, but it is difficult to obtain high-purity succinic acid. However, BPM-AEM-CEM-BPM BMED had a high current efficiency (90%) and low energy consumption (2.3 kW h/kg). An integrated technology of ED and BMED (Figure 9) was used by Ferrer et al. [74] to regenerate formic acid from a sodium formate and sodium hydroxide containing wastewater. ED was used to concentrate sodium formate, a three-chamber BMED was used to recover formic acid and NaOH from concentrated sodium formate, and a 30% formic acid was obtained with a current efficiency of 80% under a current density of 500 A m\(^{-2}\). Alvarez et al. [75] recovered salicylic acid (4.5 g L\(^{-1}\)) in a three-chamber BMED. Wang et al. [76] used a three-chamber BMED to recover three amino acids with similar structures but different methylation groups (N-methyl glycine, N,N-dimethylglycine, and N,N,N-trimethyl glycine). The effects of feed mass concentration and current density on separation performance were analyzed in terms of molecular size, molecular structure, ion concentration, and the interaction between the amino acid and the membrane. In addition, 99.2% of itaconic acid was recovered from an itaconic acid sodium solution by Komáromy in a three-chamber BMED system (Figure 10) [77], and 92% of xylonic acid was obtained from a 100 g/L sodium xylate fermentation broth by Cao et al. [78] in a three-chamber BMED system.

The integration of BMED with other processes is also used to recover organic acids and bases. Prochaska et al. [55] proposed a new method (Figure 11) based on nanofiltration, BMED, and reactive extraction techniques for the recovery of fumaric acid from a fermentation broth of glycerol biotransformation, and 95% of fumarate can be concentrated and converted to fumaric acid.
Membranes 2022, 12, x FOR PEER REVIEW 10 of 23

[74] to regenerate formic acid from a sodium formate and sodium hydroxide containing wastewater. ED was used to concentrate sodium formate, a three-chamber BMED was used to recover formic acid and NaOH from concentrated sodium formate, and a 30% formic acid was obtained with a current efficiency of 80% under a current density of 500 A m\(^{-2}\). Alvarez et al. [75] recovered salicylic acid (4.5 g L\(^{-1}\)) in a three-chamber BMED. Wang et al. [76] used a three-chamber BMED to recover three amino acids with similar structures but different methylation groups (N-methyl glycine, N, N-dimethylglycine, and N,N,N-trimethyl glycine). The effects of feed mass concentration and current density on separation performance were analyzed in terms of molecular size, molecular structure, ion concentration, and the interaction between the amino acid and the membrane. In addition, 99.2% of itaconic acid was recovered from an itaconic acid sodium solution by Komáromy in a three-chamber BMED system (Figure 10) [77], and 92% of xylonic acid was obtained from a 100 g/L sodium xylate fermentation broth by Cao et al. [78] in a three-chamber BMED system.

Figure 7. Schematic of the EDBM stack configuration for producing organic acids [72].

Figure 8. Schematic overview of the three configurations used to convert sodium succinate to succinic acid [73].

Figure 9. Global process for sodium formate splitting into formic acid and sodium hydroxide [74].
Figure 9. Global process for sodium formate splitting into formic acid and sodium hydroxide [74].

Figure 10. Scheme of the membrane module in the BMED and the predominant transport mechanisms during the separation, C1: NaOH compartment; D2: itaconic acid compartment; C2: itaconic acid sodium compartment [77].

The integration of BMED with other processes is also used to recover organic acids and bases. Prochaska et al. [55] proposed a new method (Figure 11) based on nanofiltration, BMED, and reactive extraction techniques for the recovery of fumaric acid from a fermentation broth of glycerol biotransformation, and 95% of fumarate can be concentrated and converted to fumaric acid.

Figure 11. Hybrid system for the separation of fumaric acid from a fermentation broth [55].

3. CO2 Capture

Global warming and carbon emissions have become a global problem, and carbon capture and storage are recognized as effective methods to reduce carbon emissions [79,80]. CO2 can be captured directly from industrial sources by postcombustion capture, precombustion capture, or the combustion of fossil fuels in pure oxygen environments [79] (Figure 12). Among them, postcombustion chemical absorption capture is the most mature technology [81–83]; however, the energy for the regeneration of capture reagents is high [84], which accounts for 70% of the cost of CO2 capture [85]. In the storage process, CO2 emitted from point sources can be captured and transported to a storage site, and the liquid CO2 can be injected into the ground or seawater [79]. Similarly, storage technology also involves the problems of high cost and energy consumption. It is, therefore, necessary to develop new technology to capture CO2.
Figure 12. Illustration showing different approaches for capturing CO₂ from industrial sources [79].

EDBM was demonstrated to be an effective method to capture CO₂ from flues [86–88] and the atmosphere [80,89]. The main principle of CO₂ capture by BMED is the absorption ability of bases for CO₂, which includes the three steps shown in Figure 13 [87]. First, the CO₂ from the flue is absorbed by NaOH to generate a carbonate solution (Equation (10)); second, the carbonate solution is sent to the BMED system, where NaOH is regenerated and gaseous CO₂ is recovered (Equations (11) and (12)); third, the regenerated NaOH is used to capture CO₂. However, the CO₂ recovery is only 40–60% [87,88,90]. To increase CO₂ recovery, Valluri et al. [84] improved the method by allowing sulfuric acid to react with sodium bicarbonate to produce sodium sulfate, and then using BMED to convert sodium sulfate to NaOH (Figure 14). In this way, 100% of CO₂ was recovered, and energy consumption as low as 1.18 MJ/kg CO₂ was recovered with a current efficiency of 91.2%.

\[
\text{NaOH} (aq) + \text{CO}_2 (g) \rightarrow \text{HCO}_3^- (aq) + \text{Na}^+ (aq) \tag{10}
\]

\[
\text{HCO}_3^- (aq) + \text{H}^+ (aq) \rightarrow \text{H}_2\text{O} + \text{CO}_2 (g) \uparrow \tag{11}
\]

\[
\text{Na}^+ + \text{OH}^- \rightarrow \text{NaOH} \tag{12}
\]

For the capture of CO₂ from the atmosphere, Zhao et al. [89] developed a new seawater carbon capture technology. BMED was combined with a crystallizer to avoid the precipitation of calcium ions on the membrane surface during seawater treatment. The results show that decalcification, carbon fixation, and desulfurization can reach 94.52%, 31.41% and 100%, respectively. However, the decalcified seawater still contains abundant precious magnesium resources, and the CO₂ in the flue gas is only partially mineralized. Chen et al. [91] integrated BMED into a crystallizer to prevent the nucleation of MgCO₃·3H₂O and the membrane fouling problem (Figure 15), the CO₂ fixation rate increased to 50.9%, and the magnesium recovery rate was 56.7%. Jiang et al. [80] integrated a BMED with a hollow fiber membrane (HFM) to capture CO₂ due to HFM not only physically separating CO₂ from liquid, but also to have a large mass transfer area [92]. The results showed that the energy consumption decreased to 2 MJ/kg CO₂ (including heat stable salt removal). Ruan et al. [93] also integrated BMED and HFM to capture CO₂. BMED was used to generate HCl and NaOH. HCl can be recycled to adjust the pH, and NaOH can be directly used to absorb CO₂. Under optimal experimental conditions, the CO₂ removal rate can reach 90.9%. Jiang et al. [94] used BMED to simultaneously capture CO₂ and extract methionine from
methionine salts. The methionine extraction rate was 99.57%, and the energy consumption for capturing 1 kg CO₂ was 7.0 kWh.

\[
\text{CO}_2 + \text{NaOH} \rightarrow \text{NaHCO}_3
\]

\[
\text{NaHCO}_3 \rightarrow \text{HCO}_3^- + \text{H}^+
\]

Regenerated and gaseous CO₂ is recovered (Equations (11) and (12)); third, the regenerated CO₂ and extract methionine from methionine salts. The methionine extraction rate was 99.57%, and the energy consumption for capturing 1 kg CO₂ was 7.0 kWh.

\[
\text{NaOH} \rightarrow \text{H}_2\text{O} + \text{CO}_2
\]

Figure 13. CO₂ absorption and recovery process [87].

Figure 14. Diagram of continuous CO₂ capture and regeneration with EDBM system. CO₂ is captured with NaOH solution and then regenerated by reacting with H₂SO₄; the resultant Na₂SO₄ solution is subjected to electrodialysis with a bipolar membrane to produce acid and base. The base (NaOH) is circulated back to capture additional CO₂ [84].

Figure 15. Experimental schematic diagram for magnesium extraction and CO₂ mineralization [91].
4. Ammonia Nitrogen Production and Recovery

With the rapid development of the economy and industrialization, industrial wastewater containing ammonia is continuously discharged into the environment, causing serious environmental problems [95]. According to the study by Erisman et al. [96], half of the NH₃ produced enters into the environment, leading to eutrophication and a subsequent loss of biodiversity. Therefore, ammonia pollution has become a serious environmental problem in many industrialized countries, and it is urgent to develop effective ammonia removal technologies. Nanofiltration, reverse osmosis, and biodegradation technologies have been studied to treat ammonium-containing wastewater [97–99], but these methods involve high energy consumption, secondary pollution, and high costs.

In recent years, BMED has often been used to recover ammonia from wastewater. Linden et al. [100] recovered HCl and NH₃·H₂O from simulated NH₄Cl wastewater by BMED (Figure 16). The effects of initial NH₄Cl concentration, current density, salt solution volume, initial acid–base concentration, and membrane stack structure on the yields of NH₃ were investigated. The total ammonia removal efficiency was between 85% and 91%, and the energy consumption was stable at 19 MJ kg⁻¹ of nitrogen, which is more competitive than ED combined with added chemicals (22 MJ kg⁻¹ of nitrogen). The effects of humic acid, Mg²⁺, and Ca²⁺ on the removal of ammonium were investigated by Zhang et al. [101], with the results showing that humic acid and a high concentration of Mg²⁺ and Ca²⁺ has a significant effect on ammonium removal: more than 86% of ammonium was removed from a leachate collected from a local landfill. In addition, Ferrari et al. [102] combined an on-site BMED with two liquid/liquid membrane contactors to recover ammonia from an anaerobic fermentation broth. Graillon et al. [103] found that a BMED system is not suitable for recovering nitric acid and ammonia from an ammonium nitrate solution; they proposed a two-step process instead. First, NaOH is added to the ammonium nitrate solution and ammonia is stripped, then the obtained sodium nitrate solution is treated by BMED to regenerate nitric acid and NaOH in a second step. However, this increases the operational difficulty and cost. Ali et al. [104] achieved 83% recovery of ammonium from an ammonium nitrate solution using an integrated technology of BMED and continuous in situ ammonia stripping. The different results may be caused by the differences in the BMED configuration and operation process.

![Figure 16](image-url)

**Figure 16.** The membrane and (flow) cell sequence in the BMED and the intended ion transport (electromigration and water dissociation) as a result of the applied current. In the acid, H⁺ and HCO₃⁻ are combined and react to CO₂, while in the base, OH⁻ and NH₄⁺ are combined and react to NH₃. At the cathode, NH₄⁺ is transported to the electrode rinse, while at the anode, both Na⁺ and NH₄⁺ are transported to the base, resulting in the accumulation of NH₄⁺ in the electrode rinse and the washing out of Na⁺ to the base [100].
From the above, we note that ammonia can be recovered from ammonium-containing wastewater, but the phenomena of \( \text{OH}^- \) leakage, dissolved ammonia diffusion, and ionic diffusion from the base to the diluent occur during the BMED process, which can decrease the current efficiency. With the extension of the experimental time and the increase in concentration gradients between the diluent and concentrated compartments, the current efficiency decreased from 69% to 54% [100]. This is the deficiency of BMED technology in the treatment of ammonium-containing wastewater.

5. Ion Removal and Recovery from Wastewater

With the improvement of environmental standards and the shortage of resources, the removal and recovery of metals and valuable ions from wastewater have both environmental protection and economic benefits. Heavy metals are a class of harmful pollutants, which are toxic, carcinogenic, nonbiodegradable, and persistent in the environment and organisms [105]. Once they enter the food chain, they accumulate in the human body and lead to serious health problems [104]. The most common method for removing heavy metals from wastewater is chemical precipitation, but a large amount of sludge can be generated that is hard to treat [105]. Wu et al. [106] used an improved BMED system combined with \( \text{H}_2\text{O}_2 \) oxidation to recover \( \text{Cr}(\text{III}) \) from a sodium chromate solution, and 87.8% of \( \text{Cr}(\text{III}) \) was recovered. Raffinate produced during the hydrometallurgical processing of copper ore has strong acidity and a high content of heavy metals (iron, zinc, copper, etc.), and so is difficult to treat. Liu et al. [107] found that 99.3% of iron, 99.1% of zinc, 99.0% of copper, 84.9% of nickel, 70.6% of chromium, 95.8% of cadmium, and 94.8% of arsenic can be removed, and 85.9% of \( \text{SO}_4^{2-} \) can be recovered in the form of \( \text{H}_2\text{SO}_4 \), in a BMED system (Figure 17). Liu et al. [108] also used a BMED system to remove arsenic and cationic metals from copper slag produced during copper ore hydrometallurgy, with only a small amount of stable residual metals remaining in copper slag after treatment.

**Figure 17.** Schematic representation of the BMED experimental setup for treating raffinate. AC, anode chamber; RC, raffinate chamber; HMC, heavy metal chamber; CC, cathode chamber; AEM, anion-exchange membrane; CEM, cation-exchange membrane; BPM, bipolar membrane [107].

In recent years, BMED has often been used to recover boron and lithium from solutions in the form of \( \text{H}_2\text{BO}_3 \) and \( \text{LiOH} \). Sun et al. [109] introduced a QGO-P84 membrane into BMED to recover boron from a synthetic model solution (\( \text{Na}_2\text{B}_4\text{O}_7\cdot10\text{H}_2\text{O} \), 1000 mg B/L); the recovery rate of boron and the energy consumption were 94.9% and 26.16 kW h/kg, respectively. In the study by Jarma et al. [110], 38.8% of boron and 50.2% of lithium were
recovered in a BMED system. İpekçi et al. [111] also used a BMED system to separate and recover boron and lithium from aqueous solutions (Figure 18). The results showed that the separation efficiency and recovery of boron and lithium increased when the potential increased from 15 V to 25 V under a solution flow rate of 50 L/h, and the removal and recovery rates were 74.4% and 59%, while those of lithium were 99.0% and 73.0%, respectively. İpekçi et al. [112] separated and recovered lithium and boron from an aqueous solutions using a BMED. The separation rates of boron and lithium were 86.9% and 94.7%, respectively, with a specific energy consumption of 7.9 kWh/m$^3$. In the study by Bunani et al. [113], the separation and recovery of lithium were 99.6% and 88.3%, respectively, while those of boron were 72.3% and 70.8%, respectively. Bunani et al. [114] recovered 39.1% of boron and 20.0% of lithium using a BMED system. In the study by Hung et al. [115], the removal and recovery rates of boron were 98.6% and 86.5%, respectively, in a BMED system.

From the above, we conclude that BMED can be used to remove and recover heavy metals from wastewater. Additionally, the recovery of boron and lithium from solutions using a BMED system has good application prospects. It was also found that the removal and recovery of boron and lithium are different in different studies, mainly because of difference in BMED size, membrane performance, wastewater properties, and operating conditions. The studies on boron and lithium removal and recovery are summarized in Tables 2 and 3, respectively.

Table 2. Separation and recovery of boron from aqueous solutions using BMED.

| Method          | Operating Conditions                                      | Boron Concentration | Efficiency | References |
|-----------------|----------------------------------------------------------|---------------------|------------|------------|
| intermittent BMED | voltage: 12 V, current density: 6.36 A/m$^2$, pH: 9.5–10.5, solution flow rate: 36 L/h | 680 mg B/L          | $S_B = 98.6\%$ $\beta_B = 86.5\%$ | [115] |
| Continuous BMED | Voltage: 12 V, current density: 6.36 A/m$^2$, pH: 9.5–10.5, solution flow rate: 36 L/h, reaction time: 5 cycle | 612 mg B/L          | $S_B = 98.53\%$ $\beta_B = 81.2\%$ | [115] |

Figure 18. The flow scheme of a BMED system [111].
Table 2. Cont.

| Method          | Operating Conditions                        | Boron Concentration | Efficiency | References |
|-----------------|---------------------------------------------|---------------------|------------|------------|
| BMED            | voltage: 30 V, reaction time: 3 h, membrane: QGO-P84 membrane | 1000 mg B/L         | $S_B = 76.6\%$ | [109]      |
|                 | voltage: 30 V, reaction time: 3 h, membrane: Commercial membrane CJMA-3 | 1000 mg B/L         | $S_B = 51.6\%$ | [109]      |
|                 | voltage: 15 V, sample solution: 0.5 L 3 mM HCl-3 mM NaOH membrane: PC-bip membranes | 850 mg B/L         | $S_B = 72.3\%$, $\beta_B = 70.8\%$ | [113]      |
|                 | voltage: 30 V, type of membrane: AHA membranes | 1000 mg B/L         | $S_B = 97.8\%$, $\beta_B = 39.1\%$ | [114]      |
|                 | voltage: 30 V, sample solution: 2 L 5 mM HCl-5 mM NaOH | 1000 mg B/L         | $S_B = 86.9\%$, $\beta_B = 50.0\%$ | [112]      |
|                 | voltage: 20 V, sample solution: 0.05 mol/L H$_3$BO$_3$-0.05 mol/L LiOH solution flow rate: 45–50 L/h, membrane: PC-Cell ED 640.04 model | 924 mg B/L, 313 mg Li/L | $S_B = 77.5\%$, $\beta_B = 54.0\%$ | [110]      |
|                 | voltage: 20 V, sample solution: 0.05 mol/L H$_3$BO$_3$, 0.05 mol/L LiOH solution flow rate: 45–50 L/h, membrane: Mega EDR-Z-Full-V4 model | 976 mg B/L, 314 mg Li/L | $S_B = 81.0\%$, $\beta_B = 38.8\%$ | [110]      |
|                 | voltage: 25 V, sample solution: 3 mM HCl-3 mM NaOH solution flow rate: 50 L/h, membrane: Mega EDR-Z-FULL-V4 model | $812 \pm 56.15$ mg B/L | $S_B = 74.0\%$, $\beta_B = 59.0\%$ | [111]      |

$S_B$: Separation rate of boron; $\beta_B$: Recovery rate of boron.

Table 3. Separation and recovery of lithium from aqueous solutions using BMED.

| Method          | Operating Conditions                        | Feed Solution | Efficiency | References |
|-----------------|---------------------------------------------|---------------|------------|------------|
| BMED            | Voltage: 15 V, sample solution: 0.5 L 3 mM HCl, 3 mM NaOH membrane: PC-bip membranes | 250 mg Li/L   | $S_{Li} = 99.6\%$, $\beta_{Li} = 88.3\%$ | [113]      |
|                 | Voltage: 30 V, sample solution: 0.1 M HCl, 0.1 M NaOH membrane: AHA BP-1E membranes | 340 mg Li/L   | $S_{Li} = 97.8\%$, $\beta_{Li} = 20.0\%$ | [114]      |
|                 | Voltage: 30 V, sample solution: 2 L 5 mM HCl, 5 mM NaOH | 340 mg Li/L   | $S_{Li} = 94.7\%$, $\beta_{Li} = 62.0\%$ | [112]      |
|                 | Voltage: 20 V, sample solution: 0.05 mol/L H$_3$BO$_3$, 0.05 mol/L LiOH solution flow rate: 45–50 L/h, membrane: PC-Cell ED 640.04 model | 313 mg Li/L | $S_{Li} = 99.8\%$, $\beta_{Li} = 86.4\%$ | [110]      |
|                 | Voltage: 20 V, sample solution: 0.05 mol/L H$_3$BO$_3$, 0.05 mol/L LiOH solution flow rate: 45–50 L/h, membrane: Mega EDR-Z-Full-V4 model | 314 mg Li/L | $S_{Li} = 99.8\%$, $\beta_{Li} = 50.2\%$ | [110]      |
|                 | Voltage: 25 V, sample solution: 3 mM HCl, 3 mM NaOH solution flow rate: 50 L/h, membrane: Mega EDR-Z-FULL-V4 model | $256 \pm 33.11$ mg Li/L | $S_{Li} = 99.0\%$, $\beta_{Li} = 73.0\%$ | [111]      |

$S_{Li}$: Separation rate of lithium; $\beta_{Li}$: Recovery rate of lithium.
6. Conclusions

At present, BMED technology has been widely used for recovering NaCl, NaSO\textsubscript{4}, and NaNO\textsubscript{3} salts in the form of acids and bases. In terms of organic acids, after more than 10 years of research and development, it has moved toward large-scale production. CO\textsubscript{2} capture, ammonia nitrogen recovery, wastewater ion removal and recovery are still at the lab scale; however, with increased attention being paid to these fields, it can be speculated that BMED technology will have good application.

In addition, BMED has some problems that limit its development, such as a high preparation cost, and membrane fouling and ion leakage during operation. The cost and performance of BMED depend on the membrane characteristics, feed conditions, required product quality, and parameter design such as stack structure and current density. The problem of membrane fouling during operation can be solved through modifications to the membrane hydrophilicity, charge, and roughness by adding modified components (such as nanoparticles), by pretreating the raw material solution (such as using chemical precipitation, coagulation, filtration, and other methods to reduce the solution ion concentration), and by changing the operating conditions (such as the feed solution pH, raw material solution concentration, feed speed, and other factors). To solve the problem of ion leakage, an acid-blocking membrane can be used to block the migration of H\textsuperscript{+}. H\textsuperscript{+} migration can also be reduced by controlling the cell voltage, current density, and salt compartment solution pH. Alternatively, AEM can be added to the three-chamber BMED to reduce the competitive migration of H\textsuperscript{+} with other cations. Although BMED has some deficiencies, its characteristics, such as environmental friendliness, no need to add chemical reagents, small footprint, high efficiency, and simple operation, mean it has been widely used in the field of environmental protection and resources recovery. It can be predicted that with the gradual deepening of the research on BMED, it will be applied in more fields.

Author Contributions: Conceptualization, Y.L. (Yaoxing Liu) and J.S.; writing—original draft preparation, Y.L. (Yu Luo); writing—review and editing, B.V.d.B.; funding acquisition, Y.L. (Yaoxing Liu). All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Fujian Provincial Department of Science and Technology grant number [2021J01194].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kumar, M.; Khan, M.A.; Al-Othman, Z.A.; Choong, T.S.Y. Recent Developments in Ion-Exchange Membranes and Their Applications in Electrochemical Processes for in situ Ion Substitutions, Separation and Water Splitting. *Sep. Purif. Rev.* 2013, 42, 181–261. [CrossRef]

2. Xu, T. Ion exchange membranes: State of their development and perspective. *J. Membr. Sci.* 2005, 263, 1–29. [CrossRef]

3. Khan, M.I.; Zheng, C.; Mondal, A.N.; Hossain, M.M.; Wu, B.; Emmanuel, K.; Wu, L.; Xu, T. Preparation of anion exchange membranes from BPPO and dimethylethanolamine for electrodialysis. *Desalination* 2017, 402, 10–18. [CrossRef]

4. Arana Juve, J.-M.; Christensen, F.M.S.; Wang, Y.; Wei, Z. Electrodialysis for metal removal and recovery: A review. *Chem. Eng. J.* 2022, 435, 134857. [CrossRef]

5. Kumar, A.; Phillips, K.R.; Cai, J.; Schroder, U.; Lienhard, J.H.t. Integrated Valorization of Desalination Brine through NaOH Recovery: Opportunities and Challenges. *Angew. Chem. Int. Ed. Engl.* 2019, 58, 6502–6511. [CrossRef]

6. Zhao, Y.; Li, X.; Shen, J.; Gao, C.; Van der Bruggen, B. The potential of Kevlar aramid nanofiber composite membranes. *J. Mater. Chem. A* 2020, 8, 7548–7568. [CrossRef]

7. Gurreri, L.; Tamburini, A.; Cipollina, A.; Micale, G. Electrodialysis Applications in Wastewater Treatment for Environmental Protection and Resources Recovery: A Systematic Review on Progress and Perspectives. *Membranes* 2020, 10, 146. [CrossRef]

8. Frielle, V.J. Preparation and characterization of bipolar ion exchange membranes. *Phys. Chem. 1956*, 60, 435–439. [CrossRef]

9. Bauer, B.; Gerner, F.J.; Strathmann, H. Development of bipolar membranes. *Desalination* 1988, 68, 279–292. [CrossRef]

[CrossRef]
10. Wang, Y.; Huang, C.; Xu, T. Which is more competitive for production of organic acids, ion-exchange or electrodialysis with bipolar membranes? J. Membr. Sci. 2011, 374, 150–156. [CrossRef]
11. Coria, G.; Sirés, I.; Brillas, E.; Nava, J.L. Influence of the anode material on the degradation of naproxen by Fenton-based electrochemical processes. Chem. Eng. J. 2016, 304, 817–825. [CrossRef]
12. Vasilie, S.; Manea, F.; Baciu, A.; Pop, A. Dual use of boron-doped diamond electrode in antibiotics-containing water treatment and process control. Process Saf. Environ. Prot. 2018, 117, 446–453. [CrossRef]
13. Pärnamäe, R.; Mareev, S.; Nikonenko, V.; Melnikov, S.; Sheldeshov, N.; Żabolotski, V.; Hamelers, H.V.M.; Tedesco, M. Bipolar membranes: A review on principles, latest developments, and applications. J. Membr. Sci. 2021, 617, 118538. [CrossRef]
14. Xu, T.W.; Huang, C.H. Electrodialysis-Based Separation Technologies: A Critical Review. Sep. Purif. Technol. 2008, 54, 3147–3159. [CrossRef]
15. Wilhelm, F.G. Bipolar Membrane Electrodialysis—Membrane Development and Transport Characteristics. Ph.D. Thesis, Twente University Press, Enschede, The Netherlands, 2001.
16. Tongwen, X. Electrodialysis processes with bipolar membranes (EDBM) in environmental protection—A review. Resour. Conserv. Recycl. 2002, 37, 1–22. [CrossRef]
17. Jaroszek, H.; Dydo, P. Ion-exchange membranes in chemical synthesis—A review. Open Chem. 2016, 14, 1–19. [CrossRef]
18. Yang, Y.; Gao, X.; Fan, A.; Fu, L.; Gao, C. An innovative beneficial reuse of seawater concentrate using bipolar membrane electrodialysis. J. Membr. Sci. 2014, 449, 119–126. [CrossRef]
19. Xu, T.; Yang, W.; He, B. Water dissociation phenomena in a bipolar membrane. Sci. China Ser. B Chem. 1999, 42, 589–598. [CrossRef]
20. Simons, R. Water splitting in ion exchange membranes. Electrochim. Acta 2013, 42, 183–203. [CrossRef]
21. Zabolotski, V.; Sheldeshov, N.; Melnikov, S. Heterogeneous bipolar membranes and their application in electrodialysis. Desalination 2014, 342, 183–203. [CrossRef]
22. Zabolotski, V.I.; Sheli'deshov, N.V.; Gnasins, N.P. Dissociation of Water Molecules in Systems with Ion-exchange Membranes. Russ. Chem. Rev. 1988, 57, 801–808. [CrossRef]
23. Gao, X.; Yang, Y.; Fu, L.; Sun, Z.; Zheng, Y.; Gao, C. Regenerating spent acid produced by HZSM-5 zeolite preparation by bipolar membrane electrodialysis. Sep. Purif. Technol. 2014, 125, 97–102. [CrossRef]
24. Zhuang, J.-X.; Chen, Q.; Wang, S.; Zhang, W.-M.; Song, W.-G.; Wan, L.-J.; Ma, K.-S.; Zhang, C.-N. Zero discharge process for foil industry waste acid reclamation: Coupling of diffusion dialysis and electrodialysis with bipolar membranes. J. Membr. Sci. 2013, 432, 90–96. [CrossRef]
25. Jiang, G.; Li, H.; Xu, M.; Ruan, H. Sustainable reverse osmosis, electrodialysis and bipolar membrane electrodialysis application for cold-rolling wastewater treatment in the steel industry. J. Water Process Eng. 2021, 40, 101968. [CrossRef]
26. Reig, M.; Casas, S.; Gibert, O.; Valderrama, C.; Cortina, J.L. Integration of nanofiltration and bipolar electrolysis for valorization of seawater desalination brines: Production of drinking and waste water treatment chemicals. Desalination 2016, 382, 13–20. [CrossRef]
27. Reig, M.; Casas, S.; Valderrama, C.; Gibert, O.; Cortina, J.L. Integration of monopolar and bipolar electrodialysis for valorization of seawater reverse osmosis desalination brines: Production of strong acid and base. Desalination 2016, 398, 87–97. [CrossRef]
28. Badruzzaman, M.; Oppenheimer, J.; Adham, S.; Kumar, M. Innovative beneficial reuse of reverse osmosis concentrate using bipolar membrane electrodialysis and electrodialloration processes. J. Membr. Sci. 2009, 326, 392–399. [CrossRef]
29. Chen, B.; Jiang, C.; Wang, Y.; Fu, R.; Liu, Z.; Xu, T. Selectrodialysis with bipolar membrane for the reclamation of concentrated brine from RO plant. Desalination 2018, 442, 8–15. [CrossRef]
30. Chen, Q.B.; Wang, J.; Liu, Y.; Zhao, J.; Li, P.F.; Xu, Y. Sustainable disposal of seawater brine by novel hybrid electrodialysis system: Fine utilization of mixed salts. Water Res. 2021, 201, 117335. [CrossRef]
31. Ilhan, F.; Kabuk, H.A.; Kurt, U.; Avsar, Y.; Gonullu, M.T. Recovery of mixed acid and base from wastewater with bipolar membrane electrodialysis—A case study. Desalin. Water Treat. 2015, 57, 5165–5173. [CrossRef]
32. Gonzalez, A.; Grageda, M.; Quispe, A.; Ushak, S.; Sistat, P.; Cretin, M. Application and Analysis of Bipolar Membrane Electrodialysis for LiOH Production at High Electrolyte Concentrations: Current Scope and Challenges. Membranes 2021, 11, 575. [CrossRef] [PubMed]
33. Kishida, M.; Harato, T.; Tokoro, C.; Owada, S. In situ remediation of bauxite residue by sulfuric acid leaching and bipolar membrane electrodialysis. Hydrometallurgy 2017, 170, 58–67. [CrossRef]
34. Erkmen, J.; Yapci, S.; Arzutuğ, M.E.; Aydin, Ö.; Ata, O.N.; Öner, M.R. Hydrofluoric acid and sodium hydroxide production by bipolar membrane electrodialysis. Desalin. Water Treat. 2015, 57, 20254–20260. [CrossRef]
35. Yao, L.; Qiu, Y.; Zhao, Y.; Tang, C.; Shen, J. A continuous mode operation of bipolar membrane electrodialysis (BMED) for the production of high-pure choline chloride from choline chloride. Sep. Purif. Technol. 2020, 233, 116054. [CrossRef]
36. Pan, J.; Hou, L.; Wang, Q.; He, Y.; Wu, L.; Mondal, A.N.; Xu, T. Preparation of bipolar membranes by electrospinning. Mater. Chem. Phys. 2017, 186, 484–491. [CrossRef]
37. Szczygielda, M.; Antczak, J.; Prochaska, K. Separation and concentration of succinic acid from post-fermentation broth by bipolar membrane electrodialysis (EDBM). Sep. Purif. Technol. 2017, 181, 53–59. [CrossRef]
39. Shen, J.; Yu, J.; Liu, L.; Lin, J.; Van der Bruggen, B. Synthesis of quaternary ammonium hydroxide from its halide salt by bipolar membrane electrodialysis (BMED): Effect of molecular structure of ammonium compounds on the process performance. J. Chem. Technol. Biotechnol. 2014, 89, 841–850. [CrossRef]

40. Baylis, A.D. Why glyphosate is a global herbicide: Strengths, weaknesses and prospects. Pest Manag. Sci. 2000, 56, 299–308. [CrossRef]

41. Woodburn, A.T. Glyphosate: Production, pricing and use worldwide. Pest Manag. Sci. 2000, 56, 309–312. [CrossRef]

42. Luo, J.; Wei, S.; Su, Y.; Chen, X.; Wan, Y. Desalination and recovery of iminodiacetic acid (IDA) from its sodium chloride mixtures by nanofiltration. J. Membr. Sci. 2009, 342, 35–41. [CrossRef]

43. Wang, X.-x.; Wang, M.; Jia, Y.-x.; Yao, T.-t. The feasible study on the reclamion of the glyphosate neutralization liquor by bipolar membrane electrodialysis. Desalination 2012, 300, 58–63. [CrossRef]

44. Shen, J.; Huang, J.; Liu, L.; Ye, W.; Lin, J.; Van der Bruggen, B. The use of BMED for glyphosate recovery from glyphosate neutralization liquor in view of zero discharge. J. Hazard. Mater. 2013, 260, 660–667. [CrossRef] [PubMed]

45. Xie, M.; Liu, Z.Y.; Xu, Y.H. Removal of glyphosate in neutralization liquor from the glycine-dimethylphosphit process by nanofiltration. J. Hazard. Mater. 2010, 181, 975–980. [CrossRef] [PubMed]

46. Meng, W.; Wang, G.; Zhang, M.; Wan, D.; Song, N.; Lei, Y.; Cheng, J.; Qu, W.; Lee, S. Generation of acid-base by bipolar membrane electrodialysis process during desalination of pesticide containing wastewater. Desalin. Water Treat. 2021, 217, 91–100. [CrossRef]

47. Haoran, Y.; Binhguang, W.; Yuming, Z.; Jiacheng, Y.; Zhihua, Y. Review on the research status of bipolar membrane electrodialysis toward the treatment of hyperhaline industrial wastewater. In Membrane Science and Technology; Elsevier: Amsterdam, The Netherlands, 2022; pp. 1–9.

48. Pinazo, J.M.; Domine, M.E.; Parvulescu, V.; Petru, F. Sustainability metrics for succinic acid production: A comparison between biomass-based and petrochemical routes. Catal. Today 2015, 239, 17–24. [CrossRef]

49. Ai, M.; Ohdan, K. Oxidative dehydrogenation of lactic acid to pyruvic acid over iron phosphate catalyst. Appl. Catal. A Gen. 1997, 150, 13–20. [CrossRef]

50. Gao, Z.; Chen, W.; Chen, X.; Wang, D.; Yi, S. Study on the Isomerization of Maleic Acid to Fumaric Acid without Catalyst. Bull. Korean Chem. Soc. 2018, 39, 920–924. [CrossRef]

51. Sang, R.; Kucmierczyk, P.; Duhren, R.; Razzaq, R.; Dong, K.; Liu, J.; Franke, R.; Jackstell, R.; Beller, M. Synthesis of Carboxylic Acids by Palladium-Catalyzed Hydroxycarbonylation. Angew. Chem. Int. Ed. Engl. 2019, 58, 14365–14373. [CrossRef]

52. Prikaznov, A.V.; Shmal’ko, A.V.; Sivaev, I.B.; Petrovskii, P.V.; Bregadze, V.V. Synthesis of carboxylic acids based on the close-decaborate anion. Polyhedron 2011, 30, 1494–1501. [CrossRef]

53. Solmi, M.V.; Schmitz, M.; Leitner, W. Chapter 6—CO₂ as a Building Block for the Catalytic Synthesis of Carboxylic Acids. In Studies in Surface Science and Catalysis; Albonetti, S., Parerathoner, S., Quadrelli, E.A., Eds.; Elsevier: Amsterdam, The Netherlands, 2019; Volume 178, pp. 105–124.

54. Handojo, L.; Wardani, A.K.; Regina, D.; Bella, C.; Kresnowati, M.; Wenten, I.G. Electro-membrane processes for organic acid recovery. R. Soc. Chem. 2019, 9, 7854–7869. [CrossRef]

55. Prochaska, K.; Staszak, K.; Wozniak-Budych, M.J.; Regel-Rosocka, M.; Adamczak, M.; Wisniewski, M.; Staniwskii, J. Nanofiltration, bipolar electrodialysis and reactive extraction hybrid system for separation of fumaric acid from fermentation broth. Bioresour. Technol. 2014, 167, 219–225. [CrossRef] [PubMed]

56. Li, Q.; Wang, D.; Wu, Y.; Li, W.; Zhang, Y.; Xing, J.; Su, Z. One step recovery of succinic acid from fermentation broths by crystallization. Sep. Purif. Technol. 2010, 72, 294–300. [CrossRef]

57. Huh, Y.S.; Jun, Y.-S.; Hong, Y.K.; Song, H.; Lee, S.Y.; Hong, W.H. Effective purification of succinic acid from fermentation broth produced by Mannheimia succiniciproducens. Process Biochem. 2006, 41, 1461–1465. [CrossRef]

58. Orjuela, A.; Yanez, A.J.; Peereboom, L.; Lira, C.T.; Miller, D.J. A novel process for recovery of fermentation-derived succinic acid. Sep. Purif. Technol. 2011, 83, 31–37. [CrossRef]

59. Jun, Y.-S.; Lee, E.Z.; Huh, Y.S.; Hong, Y.K.; Hong, W.H.; Lee, S.Y. Kinetic study for the extraction of succinic acid with TOA in fermentation broth; effects of pH, salt and contaminated acid. Biochem. Eng. J. 2007, 36, 8–13. [CrossRef]

60. Huang, C.; Xu, T.; Zhang, Y.; Xue, Y.; Chen, G. Application of electrodialysis to the production of organic acids: State-of-the-art and recent developments. J. Membr. Sci. 2007, 288, 1–12. [CrossRef]

61. Anastas, P.T.; Breen, J.J. Design for the environment and Green Chemistry: The heart and soul of industrial ecology. J. Clean. Prod. 1997, 5, 97–102. [CrossRef]

62. Bailly, M.; Roux-de Balmana, H.; Aimar, P.; Lutin, F.; Chryan, M. Production processes of fermented organic acids targeted around membrane operations: Design of the concentration step by conventional electrodialysis. J. Membr. Sci. 2001, 191, 129–142. [CrossRef]

63. Takahashi, H.; Ohba, K.; Kikuchi, K.-i. Sorption of di- and tricarboxylic acids by an anion-exchange membrane. J. Membr. Sci. 2003, 222, 103–111. [CrossRef]

64. Hübler-Beyer, É.; Belafi-Bakó, K.; Nemestöthy, N. Low-waste fermentation-derived organic acid production by bipolar membrane electrodialysis—An overview. Chem. Pap. 2021, 75, 5223–5234. [CrossRef]

65. Tongwen, X.; Weihua, Y. Citric acid production by electrodialysis with bipolar membranes. Chem. Eng. Process. Process Intensif. 2002, 41, 519–524. [CrossRef]
Huang, H.; Xiao, X.; Yan, B. Complex treatment of the ammonium nitrogen wastewater from rare-earth separation plant. Desalin. Water Treat. 2009, 8, 109–117. [CrossRef]

Erisman, J.W.; Bleeker, A.; Galloway, J.; Sutton, M.S. Reduced nitrogen in ecology and the environment. Environ. Pollut. 2007, 150, 140–149. [CrossRef] [PubMed]

De Gisi, S.; Galasso, M.; De Feo, G. Treatment of tannery wastewater through the combination of a conventional activated sludge process and reverse osmosis with a plane membrane. Desalination 2009, 249, 337–342. [CrossRef]

Ibáñez, R.; Pérez-González, A.; Gómez, P.; Urtiaga, A.M.; Ortiz, I. Acid and base recovery from softened reverse osmosis (RO) brines. Experimental assessment using model concentrates. Desalination 2013, 309, 165–170. [CrossRef]

Jin, X.; Li, E.; Lu, S.; Qiu, Z.; Sui, Q. Coking wastewater treatment for industrial reuse purpose: Combining biological processes with ultrafiltration, nanofiltration and reverse osmosis. J. Environ. Sci. 2015, 25, 1565–1574. [CrossRef]

Jin, Y.; Shi, S.; Cao, H.; Wu, X.; Zhao, Z.; Wang, L. Bipolar membrane electrodialysis for generation of hydrochloric acid and ammonia from simulated ammonium chloride wastewater. Water Res. 2016, 89, 201–209. [CrossRef]

Zhang, C.; Ding, W.; Zeng, X.; Xu, X. Recovery of ammonia nitrogen from landfill leachate using a bipolar membrane equipped electrodialysis system. Water Sci. Technol. 2020, 82, 1758–1770. [CrossRef]

Ferrari, F.; Pijuan, M.; Molenaar, S.; Duinslaeger, N.; Sleutels, T.; Kunstke, P.; Radjenovic, J. Ammonia recovery from anaerobic digester centrate using onsite pilot scale bipolar membrane electrodialysis coupled to membrane stripping. Water Res. 2022, 218, 118504. [CrossRef]

Grallion, S.; Persin, F.; Pourcelly, G.; Gavach, C. Development of electrodialysis with bipolar membrane for the treatment of concentrated nitrate effluents. Desalination 1996, 107, 159–169. [CrossRef]

Ali, M.; Rakib, M.; Laborie, S.; Viers, P.; Durand, G. Coupling of bipolar membrane electrodialysis and ammonia stripping for direct treatment of wastewaters containing ammonium nitrate. J. Membr. Sci. 2004, 244, 89–96. [CrossRef]

Eccles, H. Treatment of metal-contaminated wastes: Why select a biological process? Trends Biotechnol. 1999, 17, 462–465. [CrossRef]

Li, Y.; Shi, S.; Cao, H.; Wu, X.; Zhao, Z.; Wang, L. Bipolar membrane electrodialysis for generation of hydrochloric acid and ammonia from simulated ammonium chloride wastewater. Water Res. 2016, 89, 201–209. [CrossRef]

Zhang, C.; Ding, W.; Zeng, X.; Xu, X. Recovery of ammonia nitrogen from landfill leachate using a bipolar membrane equipped electrodialysis system. Water Sci. Technol. 2020, 82, 1758–1770. [CrossRef]

Ferrari, F.; Pijuan, M.; Molenaar, S.; Duinslaeger, N.; Sleutels, T.; Kunstke, P.; Radjenovic, J. Ammonia recovery from anaerobic digester centrate using onsite pilot scale bipolar membrane electrodialysis coupled to membrane stripping. Water Res. 2022, 218, 118504. [CrossRef]

Grallion, S.; Persin, F.; Pourcelly, G.; Gavach, C. Development of electrodialysis with bipolar membrane for the treatment of concentrated nitrate effluents. Desalination 1996, 107, 159–169. [CrossRef]

Ali, M.; Rakib, M.; Laborie, S.; Viers, P.; Durand, G. Coupling of bipolar membrane electrodialysis and ammonia stripping for direct treatment of wastewaters containing ammonium nitrate. J. Membr. Sci. 2004, 244, 89–96. [CrossRef]

Eccles, H. Treatment of metal-contaminated wastes: Why select a biological process? Trends Biotechnol. 1999, 17, 462–465. [CrossRef]

Li, Y.; Shi, S.; Cao, H.; Wu, X.; Zhao, Z.; Wang, L. Bipolar membrane electrodialysis for generation of hydrochloric acid and ammonia from simulated ammonium chloride wastewater. Water Res. 2016, 89, 201–209. [CrossRef]

Zhang, C.; Ding, W.; Zeng, X.; Xu, X. Recovery of ammonia nitrogen from landfill leachate using a bipolar membrane equipped electrodialysis system. Water Sci. Technol. 2020, 82, 1758–1770. [CrossRef]

Ferrari, F.; Pijuan, M.; Molenaar, S.; Duinslaeger, N.; Sleutels, T.; Kunstke, P.; Radjenovic, J. Ammonia recovery from anaerobic digester centrate using onsite pilot scale bipolar membrane electrodialysis coupled to membrane stripping. Water Res. 2022, 218, 118504. [CrossRef]

Grallion, S.; Persin, F.; Pourcelly, G.; Gavach, C. Development of electrodialysis with bipolar membrane for the treatment of concentrated nitrate effluents. Desalination 1996, 107, 159–169. [CrossRef]

Ali, M.; Rakib, M.; Laborie, S.; Viers, P.; Durand, G. Coupling of bipolar membrane electrodialysis and ammonia stripping for direct treatment of wastewaters containing ammonium nitrate. J. Membr. Sci. 2004, 244, 89–96. [CrossRef]

Eccles, H. Treatment of metal-contaminated wastes: Why select a biological process? Trends Biotechnol. 1999, 17, 462–465. [CrossRef]

Li, Y.; Shi, S.; Cao, H.; Wu, X.; Zhao, Z.; Wang, L. Bipolar membrane electrodialysis for generation of hydrochloric acid and ammonia from simulated ammonium chloride wastewater. Water Res. 2016, 89, 201–209. [CrossRef]

Zhang, C.; Ding, W.; Zeng, X.; Xu, X. Recovery of ammonia nitrogen from landfill leachate using a bipolar membrane equipped electrodialysis system. Water Sci. Technol. 2020, 82, 1758–1770. [CrossRef]