4
Electrodialysis in the Food Industry

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4.1
Introduction

During the last century, electrodialysis developed from a laboratory curiosity to a powerful tool that is applicable in a wide variety of industrial applications. Of special interest is the application of the variations of electrodialysis to difficult separations found in certain food industries. Electrodialysis is often the separation tool of choice in the dairy, wine, and juice and sugar industries.

The first experiments with ion-exchange membranes were performed in the early 1890s by Ostwald, and opened many opportunities for membrane-separation technology [1]. The concepts of membrane potential and the Donnan exclusion phenomenon were developed a few years later [2]. The concept of electrodialysis was introduced by Manegold and Kalauch [3] in 1940. They arranged cationic and anionic ion-exchange membranes to separate ions from water. In that same year, Meyer and Strauss expanded this to assemble many such membrane pairs into a multicell arrangement between a single pair of electrodes [4]. Using this arrangement with the newly developed polymer membranes, electrodialysis quickly became the technology of choice for commercial desalination plants. A variation of this technology, electrodialysis reversal (EDR), was developed in the 1970s to address certain problems characterizing traditional electrodialysis [5, 6]. EDR exhibited lower operating costs, especially in membrane-system maintenance, and replaced traditional electrodialysis in desalination applications. The lower operating costs associated with EDR also facilitated extension of electrodialysis to other commercial separation problems. The development of bipolar membranes in 1977 and perflouro-based membranes in 1979 further expanded the applicability of electrodialysis technology to a wide variety of industrial separations [7]. Electrodialysis in its many variations has become not only become a technology for desalination, but also a viable and cost-effective solution for separation problems throughout the dairy, juice, and wine industries. In this chapter, electrodialysis theory and applications as applied to the food industry will be discussed.

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4.2
Technology Overview

4.2.1
Principle of the Electrodialysis Process

Electrodialysis is the separation of ionic materials under the influence of an electric field in a system comprised of ion-exchange membranes arranged to make flow compartments called cells. The three types of ion-exchange membranes commonly employed in electrodialysis systems are anion-exchange membranes, cation-exchange membranes, and bipolar membranes. Anion-exchange membranes are membranes that allow anions to pass through (permeate) but do not allow cations to permeate. Cation-exchange membranes are membranes that permeate cations but not anions. An example of the action of a cation-exchange membrane is shown in Figure 4.1. Bipolar membranes (Figure 4.2) are the lamination of a cation-exchange membrane and anion-exchange membrane. They do not allow ions of either charge to permeate all the way through the membrane. Bipolar membranes are primarily used to produce acids and bases by electrolysis of salt solutions [8, 9]. Electrodialysis utilizes the chemistry of the membranes and an electrical potential to remove ions

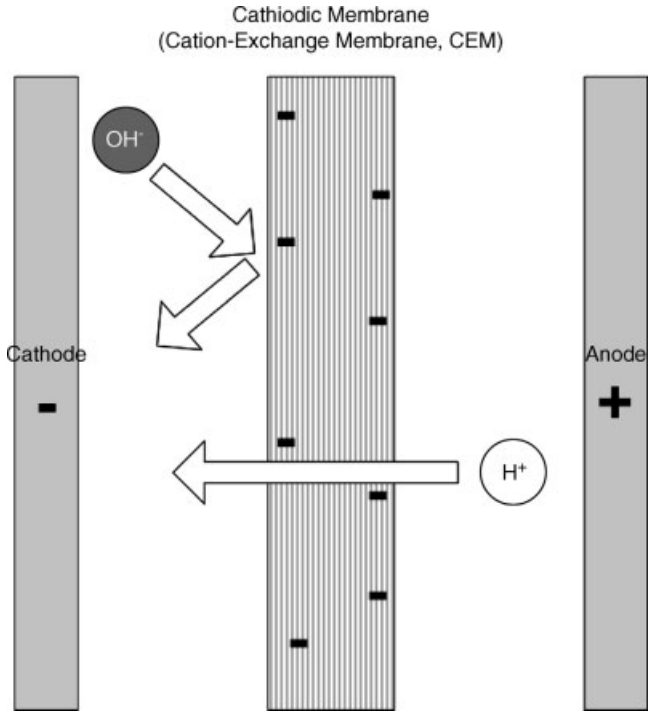


Figure 4.1 Cation-exchange membrane action.

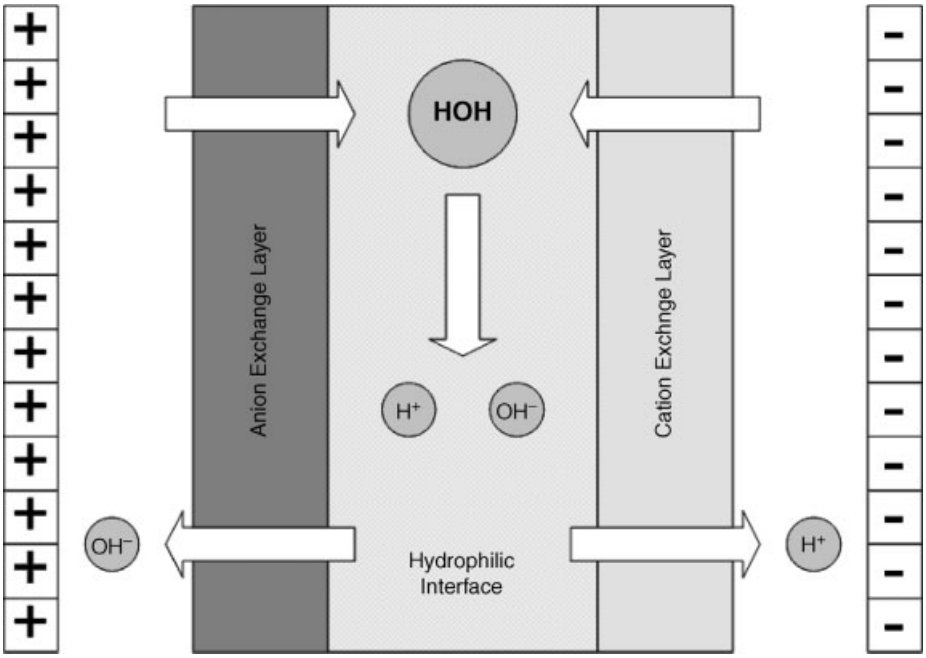


Figure 4.2 Bipolar membrane.

from solutions. A typical electrodialysis setup consists of cation- and anion-exchange membranes arranged alternately and separated slightly with some form of spacer. Each pair of cation- and anion-exchange membranes is called a cell pair. A series of cell pairs put together between two electrodes is called a stack (Figure 4.3). The number of cell pairs used in a stack depends on the requirements of the specific application and may reach as many as 500 cell pairs [10, 11].

Electrodialysis systems transport ions through the sum of two different driving forces: ion concentration gradients and electric potential gradients. The forces generated by the electrical potential gradients in electrodialysis systems are usually much larger than the forces generated by ion concentration gradients. In electrodialysis, cations and anions are transported in opposite directions; however, the fraction of electrical current carried by cations and anions is not necessarily equal. The fraction of total electric current carried by either cations or anions is called the transport number of that type of ion. The sum of all transport numbers is one in electrodialysis systems. The cation transport number is a function of the velocity of the cations (u) in the externally applied electric field and is shown in Equation 4.1. The anion transport number is a function of the velocity of the anions measured in the same direction ($-v$) and is shown in Equation 4.2 [8–10]

$$t^{+} = \frac{u}{u+v} \tag{4.1}$$

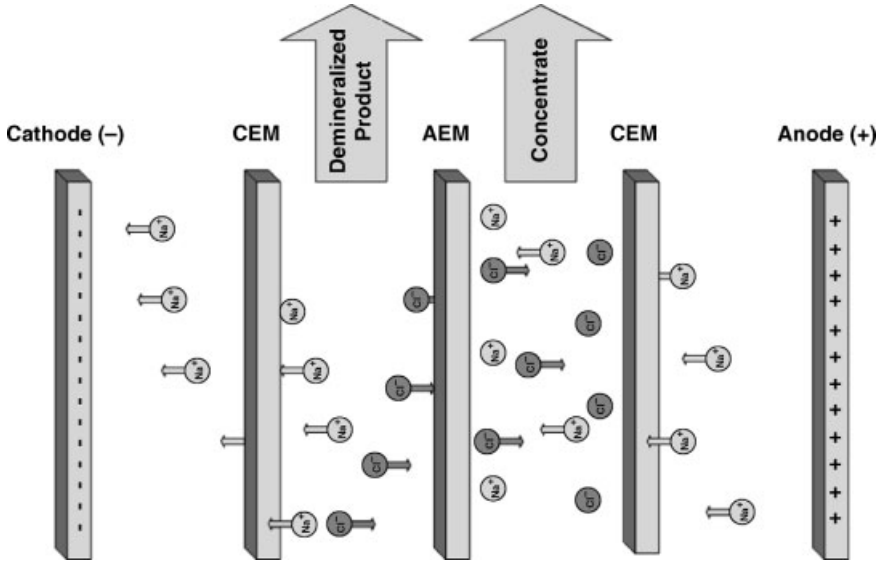


Figure 4.3 Electrodialysis stack.

$$t^{-} = \frac{v}{u+v} \tag{4.2}$$

where t^{+} is the cation transport number and t^{-} is the anion transport number. The transport numbers of ions are different for different ionic species and reflect the different sizes and charges of the ions. In electrodialysis or other membrane-separation systems, the transport number of ions having the same charge as the charge of the ion-exchange membranes approaches zero. The transport number approaches one for ions having a charge opposite of the charged group of the membrane. A transport number close to zero means the membrane does not allow ions to permeate, while a transport number close to one means the ions can pass easily through the membrane. A difference in transport number allows separations to be achieved with ion-exchange membranes.

Manipulation of concentrations of salts and ions in electrodialysis systems can help achieve the separation of interest. For instance, consider the separation of cations and anions by a cation-exchange membrane. The concentration of cation in the membrane is defined as $c^{+}_{(m)}$, the concentration of anion in the membrane is defined as $c^{-}_{(m)}$, the concentration of fixed-charged group inside the membrane is $c_{R(m)}$, and the concentration of salt in the solution is $c_{(s)}$. The mathematical expression of cation transport inside the membrane is shown in Equation 4.3 [12–14]:

$$\frac{c^{+}_{(m)}}{c^{-}_{(m)}} = \frac{1}{k}\left(\frac{c_{R^{-}(m)}}{c_{(s)}}\right)^{2} \tag{4.3}$$

where k is an equilibrium constant. Equation 4.3 shows that as the concentration of the salt in the feed solution increases, the ratio of cation concentration to anion

concentration in the membrane decreases. This means the cation-exchange membrane becomes partially permeable to anions and the overall membrane separation becomes poorer. More details about ion transport in membrane separation and electrodialysis theory can be found from a variety of sources [6, 10, 12–24].

4.2.2 System Design

4.2.2.1 Concentration Polarization, Limiting Current Density, Current Utilization, and Power Consumption

The performance of electrodialysis systems is determined by several factors. In a typical electrodialysis stack, ions migrate through a membrane but do not permeate the next membrane in the stack. For instance, cations migrate through a cation-exchange membrane but do not pass through the next anion-exchange membrane. As a result, the salt concentration increases in those compartments where the ions cannot exit, while the other compartments are continuously depleted of salts. In the typical stack arrangement, every other compartment becomes more concentrated, while the alternating compartments become less concentrated. The chambers where the salt concentration increases are called the concentrate compartments, and the chambers where the salt concentration decreases are called the diluate compartments. In a typical electrodialysis system, the efficiency of the system is usually dictated by the electrical resistance of the diluate compartments. This resistance is high because the low ion concentration in the compartment does not support electrical current conduction.

The formation of a low ion concentration boundary layer at the membrane surface also lowers the separation efficiency. The difference between the bulk solution ion concentration and the low ion concentration layer at the surface of the membrane is called concentration polarization. Performance of an electrodialysis system is limited by concentration polarization. As the ion concentration adjacent to the membrane decreases, the electrical potential must be increased to maintain the same ion flux across the membrane. As ions transport through the membrane, the concentration of ions next to the membrane surface becomes smaller. Ion transport is thus limited by the depleted layer at the membrane surface. The energy consumption per ion transported increases significantly when concentration polarization occurs. When the ion concentration at the membrane surface approaches zero, the transport rate of ions through the membrane becomes the transport rate through the boundary layer. The electric current per membrane area through the electrodialysis system at this point is called the limiting current density. Increasing the current above the limiting current density will not increase the ion transport across the membrane and this is thus wasted power. The excess power most commonly goes to the dissociation of water into hydrogen and oxygen [25, 26]. The energy used in water dissociation is wasted power, and commercial systems are operated below the limiting current density. Concentration polarization can be reduced to some extent by thoroughly mixing the salt solution in each compartment but will never be eliminated in electrodialysis systems. The adverse effects of concentration polarization significantly reduce the

performance of electrodialysis systems. If the concentration of ions in the compartment becomes very low, the internal resistance of the compartment becomes very high, and limiting current density can occur even without concentration polarization.

The limiting current density is highly specific for each electrodialysis system and can best be determined through experimentation. The limiting current density can be determined by measuring the total resistance of the stack and the pH of the diluate chamber as a function of current density. When the pH is plotted versus the reciprocal of current, a sharp decrease in pH is noted when the limiting current is reached. Similarly, when the total resistance of a stack is plotted versus the reciprocal of the current, a minimum is obtained, indicating the limiting current density. Determination of the limiting current density is rather difficult in industrial-scale electrodialysis systems and it is usually approximated in practice [9, 13, 18, 27].

The performance of an electrodialysis system is usually evaluated by the energy consumption required to perform a separation. The energy consumption (E) is a function of the voltage (V) applied across the system and the current (I) through the stack as shown in Equation 4.4

$$E = IV \tag{4.4}$$

Another way to evaluate system performance is to calculate the current utilization. Current utilization is the ratio of theoretical current required to transport charges across the membrane to the actual operating current. The theoretical current is a function of the valence (z) of the ion, the change in concentration of ions (ΔC), Faraday's constant (F), and the solution flow rate (Q) as shown in Equation 4.5

$$I_{\text{theor}} = z\Delta CFQ \tag{4.5}$$

Current utilization is always less than 100% (usually greater than 90%), this is due to many factors and the discussion of these factors is beyond the scope of this discussion. However, this is a simple calculation that allows one to determine how well an ED system is operating. Details of concentration polarization, limiting current density, power consumption, and current utilization can be found in many papers [6, 12, 13, 20, 21, 23, 28, 30–32].

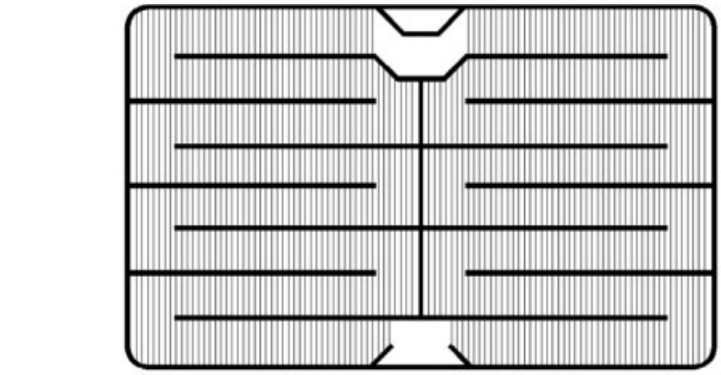
4.2.2.2 System Design and Cost Analysis

Many factors must be incorporated into the design and cost analysis of an electrodialysis system. Some general comments relating to electrodialysis design and cost analysis are made below.

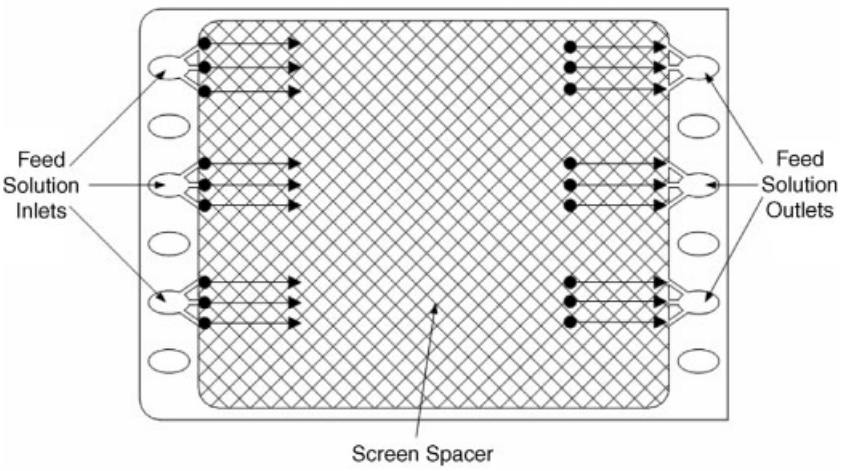
Electrodialysis can be a single-stage or multistage process, depending on the application. For either arrangement, a typical electrodialysis system consists of five components: a feed pretreatment system, a membrane stack, a power supply, a control system and a pumping system. The feed pretreatment is necessary to prevent membrane fouling by particle deposition on the membrane surface. The pretreatment process needed depends on the feed quality and is usually a combination of microfiltration or ultrafiltration and pH adjustment or addition of antiscaling chemicals. For instance, in the wine industry, the pretreatment of wine after

fermentation but before electrodialysis often includes centrifugation and reverse osmosis to remove solid particles [33, 34]. In the production of lactic acid from whey, pretreatment often consists of pH adjustment and microfiltration [35–37].

The membrane stacks in electrodialysis systems consist of up to 500 membrane cell pairs with an active membrane area of 1–2 m^2 per cell pair [13, 33, 38–41]. Between the membranes of each compartment, there is a spacer to evenly distribute the process flow. The two most common spacers used are tortuous path (Figure 4.4a) and sheet flow (Figure 4.4b). Tortuous path membranes must be thicker and sturdier than sheet-flow membranes since there is no additional spacer between the membranes in the tortuous path system. The choice of spacer is often dictated by



(a)



(b)

Figure 4.4 (a) Tortuous path stack spacer and (b) Sheet flow path stack spacer.

preference of the membrane vendor. The length of the flow path between membranes is designed as short as practically possible to decrease fluid flow resistance and pressure drop. Cleaning of an ED stack in food applications is similar to other membrane process with various acid, bases, and sanitization rinsing steps. However, since chlorine is seldom used because of membrane degradation, membrane cleaning and replacement often needs to take place more often in food applications. In theory, the electrodialysis stack can be disassembled and the membranes cleaned and replaced on site when they become heavily soiled. However, *in situ* cleaning is performed infrequently because it is difficult to reassemble an electrodialysis stack without introducing leakage. Membrane cleaning is usually done by the vendor and is performed once or twice a year, depending on the type of application [42–45].

The power supply and process control units of an electrodialysis system comprise a large portion of the capital cost of an electrodialysis system. The electric current used in electrodialysis systems is usually direct current (DC) rather than alternating current (AC). Electrodialysis systems operate at high voltage and high current, which requires stringent precautions to ensure safe operation. Such precautions include, but are not limited to, good electrical insulation around the system and periodic checks for corroded parts [10, 11, 17, 28, 46].

The last component comprising electrodialysis systems is the pumping system. Typical pressure drops in stacks vary from 15 to 30 psi for a sheet flow path cell and from 70–90 psi for a tortuous path cell [13, 18, 47]. Depending on the application, interstage pumps might be necessary for the stack. In a multistage electrodialysis system, power consumption by the pumping system is a large fraction of the plant operating cost. This power consumption fraction increases as the concentration of feed or diluate decreases, because less power is required for separations, and more power is required for mixing.

The total cost of ownership for electrodialysis systems consists of many capital and operating costs. The depreciable capital cost items in electrodialysis systems are membrane stacks, pumps, electrical equipment, and control units. The capital investment required for electrodialysis plants is dictated by the total number of ions that must be removed from the feed solution. The lifetime of membranes is usually assumed to be 5 years and the lifetime of other equipment is usually assumed to be 10 years. With these membrane lifetimes, the operating cost of electrodialysis plants is dominated by energy consumption (>90% of total operating cost) [10, 11, 20, 21, 23, 24, 48, 49]. The energy cost can be calculated from the energy required for the separation process and the energy for the pumping systems. Details of the economic analysis of electrodialysis systems can be found in the following references [6, 10–12, 20, 23, 24, 29, 32, 50].

4.3 Electrodialysis Applications in the Food Industry

The use of membranes in the food industry has increased steadily for the past 25 years. In 1988, the total annual sale of membranes and membrane modules for

food applications was estimated at about 160 million USD, or about 15% of the total annual sales of this industry. By 2001, the total annual sales increased to 400 million USD, or by 7.5% per year [51]. Membrane technologies used in the food-processing industry include reverse osmosis, ultrafiltration, microfiltration, and electrodialysis. Electrodialysis systems annual sales account for about 10% of the total membranes systems sold [9, 41, 43]. The main applications of electrodialysis are in dairy (40%) and beverages (wine, beer, fruit juices, etc.) [9, 52]. Additionally, there are emerging electrodialysis processes for the treatment and transformation of raw agricultural products into safe and well-accepted food products. Pertinent characteristics of electrodialysis systems adopted by the food industry are [13, 53–57]

- improvement of process performance and food quality in preparation of traditional food products;
- innovation of processes and products aimed at satisfying evolving food requirements related to nutrition and health;
- meeting the demands of changing regulations related to waste and waste treatment in food processes.

Electrodialysis gives the food industry three advantages as compared to competing technologies: increased food safety, economic competitiveness, and environmental friendliness. Current applications of electrodialysis in the juice, wine, and dairy industries highlight the innovation and diversity of electrodialysis in food processing.

4.3.1 Wine Industry

Electrodialysis is commonly used by the wine industry to remove tartrate salts from wine before bottling. Tartrate salts have a tendency to precipitate during storage and the precipitates decrease the quality of wine. A block diagram of a process for making wine from grape must with integrated membrane technology is shown in Figure 4.5

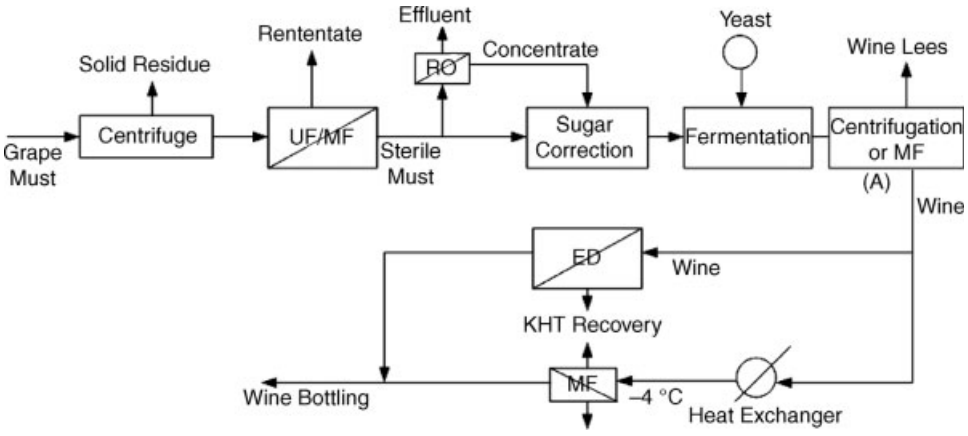


Figure 4.5 Process flow diagram for making wine from grape must.

[22, 28, 34, 54, 58, 59]. Grape must is first centrifuged to remove solid particles and then passed through either an ultrafiltration or microfiltration unit to remove microorganisms. A portion of the sterile must is then passed through a reverse osmosis unit to increase its sugar concentration. The concentrated must is then blended with the remaining must to achieve a desired sugar level before sending the must concentrate to the fermentation step. Yeast starter is added to the fermenter to convert the concentrated must to wine. The product from the fermenter is either centrifuged or filtered to remove the lees. In the last step, the wine product is either treated with electrodialysis or chilled and filtered by microfiltration to reduce the levels of tartrate salts. In Figure 4.5, electrodialysis is used to prevent the precipitation of tartrate salts in the wine product. Electrodialysis is also sometimes used before fermentation to stabilize the final product. Other salts can also be problematic in wine production. These salts are naturally present in the grape must and can be precipitated as potassium bitartrate, potassium bimalate, potassium tartrate, calcium tartrate, calcium malate, calcium succinate, and calcium oxalate [22, 33, 38, 50, 56, 58, 60, 61]. Electrodialysis removes excess salts from wines or grape juices. The amount of ions needed to be removed from the solution is dependent upon the type of wine, grapes, and type of vineyards. It is difficult to generalize the optimal amount of these ions at the various stages of the wine production. Some studies of red wine suggest that the amount of potassium should be reduced to a level of 100 to 450 mg/l [28, 34, 45, 50, 62–64], depending on the type of wine, while other studies suggest a 10% decrease in the concentration of potassium ion is enough to stabilize white wine [28, 44, 50, 56, 61].

The removal of cations increases the acidity of the wine or grapes and decreases the alcohol content of the wine [42, 47, 50, 56, 65]. Moreover, a 10% sugar loss has been reported during demineralization of must using electrodialysis [28, 42, 43, 56, 65]. The presence of sulfur dioxide helps to stabilize the wine products from spoiling due to microorganisms. However, electrodialysis systems extract HSO_3^- at a very high rate. Approximately 50–80% of the total SO_2 is eliminated from musts containing up to 850 mg l^{-1} of SO_2. For wines with a low SO_2 concentration (~100 ppm), only 20% of the SO_2 is extracted [44, 61, 65]. Sulfonic components of the must are not affected by electrodialysis and their concentration remains constant through electrodialysis [42, 44, 56, 61]. Other organic acids such as malic acid are removed at the same rate as tartaric acid [33, 34, 54]. In the presence of high tannin and anthocyanin concentrations, typical in red wines, potassium and tartaric ion removal are decreased.

Electrodialysis is also used in deacidification and acidification of grape musts and wine to harmonize the wine by adjusting the sugar content, acid content, and pH. A special configuration of electrodialysis ion substitution is used for this purpose. In ion substitution, the electrodialysis system works as an ion exchanger. Two anionic membranes are put together to create a cell pair instead of the more usual cell cation and anion membranes. Three different compartments are formed with three flow streams: acceptor, donor, and product [38]. The donor solution donates ions into the product stream while the acceptor stream receives ions from the product stream. The product stream receives ions from the donor stream and delivers different ions to

the acceptor stream. For instance, when NaOH or KOH is used as the donor stream, OH^- will replace the anion group in the feed or product stream and make the stream less acidic. It has been reported that the acid concentration in wine can be reduced from 7.0 to 3.7 g/l using deacidification electrodialysis [22, 28, 33, 42, 45, 62, 63, 66, 67]. For acidification of grape must and wines, two cation membranes are used to form the three compartments and streams. The donor stream in this case is an acidic solution. The pH of wine can be adjusted from 4.5 to 3 using an acidification electrodialysis process [28, 48, 53, 66–70].

It has been reported that the current efficiency for electrodialysis systems in grape juice and wine stabilization is between 65–75% depending on the quality of the feed [45, 48, 53, 67–69]. As addressed in the previous section, power consumption is directly proportional to the current density. For grape must and wine treatments, a current density at 100 A m^{-2} leads to an energy consumption of about 5.0 kWh kg^{-1} of K^+ removed [45, 68, 71]. The energy consumption during the electrodialysis process for concentrating must is between 3 and 4.4 kWh m^{-3} of treated must at the beginning of the concentration process. The energy consumption increases as the feed becomes more dilute and becomes 17 kWh m^{-3} during the last stages of the process [67]. It has been reported that the typical cost of electrodialysis systems sized for a production rate of 10 million gallons per year is about $400 000 with an operating cost of $0.01/l of wine. For vineyards with low capacity (less than 4500 m^3 $year^{-1}$), an electrodialysis system can be rented for less than $0.10 per bottle of wine [28, 34, 38, 61].

4.3.2 Juice and Sugar Industry

The two primary applications of electrodialysis in the juice and sugar industry are deacidification and demineralization. The juice extracts from orange, grape, pineapple, and lemon are highly acidic. Acid concentrations of 1.0–1.2% in orange, grape, and pineapple juices interfere with utilization of these juices in single-strength or concentrated forms [8, 73]. About 15–25% of the pineapple juice obtained as by-product in the pineapple canning industry is not suitable for production of single-strength or concentrated juice due to high acidity [48, 67, 69, 70, 74–76]. The sourness or sweetness in the juices is related to the ratio of soluble solids (sugars) to acids in the juice. The concentration of sugars in the fruits remains constant during the growing season but the concentration of citric acid increases during the fall and winter months. In the juice industry, the ratio of soluble solids to acid in the juice is called the Brix/acid ratio. A Brix/acid ratio of less than about 12 is undesirably sour for orange juice; a sweet orange juice has a Brix/acid ratio of 13.5–14.5 [42, 45, 67, 72, 77, 78]. A Brix/acid ratio in grapefruit juice of less than 9 is too sour for consumption; an acceptable Brix/acid ratio for grapefruit juice is about 10 to 11 [8, 42, 45, 52].

The Brix/acid ratio of sour juice can be increased to a desirable range by blending the sour juice with high naturally sweet juices that have been saved from the previous harvest season. However, there is usually not enough natural sweet juice available for blending with sour juices. There is also significant cost involved with storage of

naturally sweet juices when using the blending option. Another method to increase the Brix/acid ratio is through sugar addition. This procedure suffers from the high cost of sugar and blending equipment. Further, legal requirements mandate that canned or frozen juices to which sugar is added must be labeled "Sugar Added." The juice industry has found that sugar-added products command a lower price than products for which the label is not needed. Moreover, if the juice is exceptionally sour, the quantity of sugar needed to raise the Brix/acid ratio to acceptable levels may cause a syrupy consistency of the juice. Using alkaline materials to neutralize the acid in the juice can also increase the Brix/acid ratio. However, this method causes unacceptable changes in flavor and/or formation of undesirable precipitates.

Deacidification using electrodialysis eliminates all of these storage and legal problems. The electrodialysis stack used for deacidification of juices consists of two anion-exchange membranes. The stack formed from these cells consists of alternating diluate compartments (juice compartments) and concentrate compartments (alkali compartments). In this configuration, only anions pass through membranes and the net effect is the extraction of anions from the juice and their replacement by OH^- ions from the alkali compartment. The voltage potential is periodically reversed without interchanging the two streams (this technique is referred to as "electrodialysis reversal") to prevent colloids and solids from depositing on the surface of the membrane. The energy requirement for juice deacidification varies between 0.02 and 0.1 kWh/equiv., which is between 6 and 10 kWh m^{-1}. The current efficiency for an electrodialysis system in the deacidification of fruit juice is from 52 to 90% depending on the quality of the juice [8, 47, 52, 73, 79–81].

Cloudy or unclarified apple juice is in high demand because of its high content of dietary fiber and important nutrients. However, it is difficult to produce superior-quality cloudy juice. Cloudy apple juice is very sensitive to enzymatic browning because it contains high quantities of polyphenols and polyphenol oxidase (PPO). The enzymatic browning reaction is catalysed by PPO and coverts polyphenol to o-quinones, which then polymerize to form complex dark pigments. Therefore, the composition of the apple juice changes as the reaction occurs. Temporarily lowering the pH of apple juice to 2.0 and then readjusting the pH to normal values will irreversibly inhibit PPO activity and stabilize the juice color [82–84]. The previous approach to this process was to use hydrochloric acid and caustic soda to adjust the pH of the juice; however, this treatment results in the formation of salts that adversely affect the flavor of the apple juice. Acidification of apple juices by bipolar membrane electrodialysis avoids the formation of flavor-degrading salts. As discussed previously, bipolar membranes are membranes having the characteristics of both cationic and anionic membranes. Bipolar membranes are used to produce acids and bases by electrodialysis. With this unique characteristic, bipolar membrane electrodialysis is a perfect tool to adjust the pH in cloudy apple juices for enzyme inhibition, as shown in Figure 4.6. In this electrodialysis system, potassium chloride solution is used as the concentrate solution. Potassium ions in the juice migrate across the cationic membrane into the concentrate compartment and are replaced by hydrogen ions formed at the bipolar membrane. Using this configuration, the pH of apple juice can be lowered from 3.5 to 2, and the enzymatic activity decreases significantly.

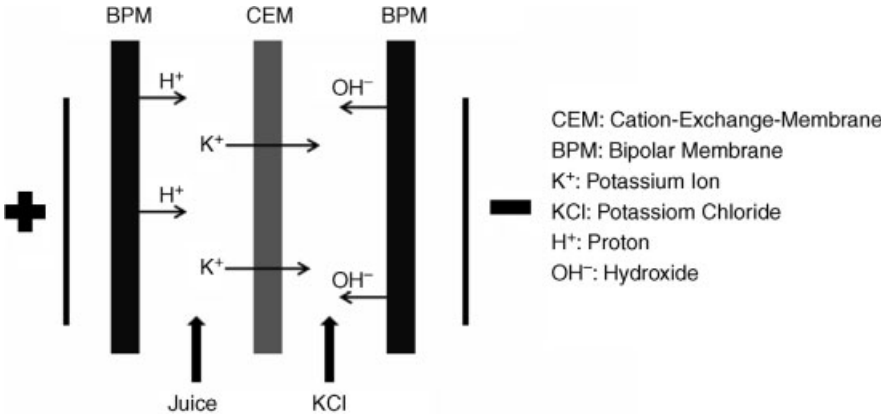


Figure 4.6 pH Adjustment of apple juice.

The energy consumption for this process ranges from 20–97 kWh/m^3 of juice. The current efficiency based on the amount of potassium removed from apple juice solution ranges from 60–90%, depending on the quality of the apple juice [53, 66, 69, 70, 82–84].

Another important application of electrodialysis in juice and sugar industries is to reduce the mineral content (demineralize) of sugar sirup. It has been known for more than 40 years that alkali metal cations are highly melassigenic; they hold sugar in the molasses and prevent it from being recovered as crystalline white sugar. Many authors quantify the melassigenic effect of the alkali and alkaline-earth ions. The affects of these ions decreases in the order K > Na > Ca > Mg, with the potassium and sodium ions much more melassigenic than magnesium ions. The raw juice of sugar beet or sugar cane contains up to 3.5% ionized materials [57, 77, 85–91]. These ionized impurities inhibit the crystallization of sugar and cause scaling of the tubes in the evaporators. It has been shown that if the ions are removed from the juice, about 5% more sugar is recovered from each ton of cane or beets, and scaling in the evaporator tubes is reduced [11, 42, 89, 92]. Several technologies have been employed in the sugar industry to remove melassigenic ions: ion-exchange resins, synthetic adsorbents, coagulants and membranes. However, these technologies are costly and have a short lifetime in high sugar content solutions. Electrodialysis systems containing cation and anion membranes in alternating order (the usual configuration) are used in the demineralization of sugar sirup. A problem encountered with the use of electrodialysis in ion removal from sugar juices is a high fouling potential in systems that are not properly cleaned. Fouling in these systems is caused by negatively charged organic materials in the sugar juice. These materials deposit on the surface of the membranes and increase the resistance of the membranes, which in turn decreases the current efficiency. Membrane fouling reduces the production rate and increases the energy consumption costs. A properly working and fouling-free electrodialysis system requires about 1.10 kWh kg^{-1} of salt removed for juice applications [80, 85, 93]. The energy savings by using electrodialysis is 440 kWh ton^{-1}

of sugar produced [11, 57, 85]. The typical current efficiency of electrodialysis systems in this application is between 40–45%, depending on the sugar content of the sirup [17, 42, 44, 89, 92].

Recent studies indicate that electrodialysis use will recover sugar and potassium from blackstrap molasses. Blackstrap molasses is the liquid left from the crystallization of sugar. Blackstrap molasses contains about 55% sucrose as invert sugar, 10% ash, 5–10% nonsugar organic materials, and 18–25% water [85, 86, 89, 92]. The inorganic and nonsugar organic materials inhibit the crystallization of the sucrose. Blackstrap molasses is usually sold at low price for cattle feed or for alcohol production. The ash in blackstrap is mostly potassium compounds and is valuable for fertilizer production. At current prices, blackstrap molasses is much lower in value than the sucrose and potassium contained in the solution. Electrodialysis for the recovery of potassium and sugar from blackstrap molasses has the potential to become a high value added process for the sugar industry. Research and economic investments in this emerging technology continues.

4.3.3
Dairy Industry

Electrodialysis is used to demineralize and acidify whey in the dairy industry. Whey is the fluid by-product in cheese manufacture. In the United States, cheese manufacturers produce about 25 billion pounds of whey yearly. The whey contains highly nutritious materials: 12% protein, 1% fat, 70–75% lactose, 8–10% ash, and 0.1–1% lactic acid (based on dry weight). Whey is a good source of protein, milk, sugar, and vitamins; however, its high ash content makes its unsuitable as human food [35, 36, 94, 95]. There are two different types of whey: one from the curd in cheese making and one from casein production [43–45, 47, 72, 96, 97]. The compositions of the two types are similar.

In spite of its high ash content, a portion of whey is dried and sold at low prices as an additive in animal feed. Ultrafiltration is used to recover protein from whey. The product of using this technology is high-grade protein suitable as human food. However, the large amount of lactose in the ultrafiltration permeate still results in a serious waste-disposal problem. The worldwide capacity for whey desalting by electrodialysis is about 100 000 tons per year of 90% demineralized whey powder from over 3 million tons of whey. This requires over 25 000 m^3 of installed membrane area and represents a large use of electrodialysis in the food industry [96].

Whey demineralizitation uses a conventional electrodialysis system, where cation- and anion-exchange membranes are arranged in alternate order to form cell pairs. The most common feed for these systems is preconcentrated sweet whey (18–28%) [94, 95] In other commercial applications, acid whey, skim milk, reduced-lactose whey, milk and whey ultrafiltration permeates are used as feed materials. Removing ash from whey with electrodialysis produces whey with up to 90% demineralization [8, 41, 98, 99]. The limiting factor in the demineralization of whey is the decrease in electrical conductivity of low ionic concentration solutions. For instance, the conductivity of whole milk is about 5 $mS\,cm^{-1}$, while fully

demineralized milk and whey have negligible electrical conductivity [64]. Concentrated whey as an electrodialysis feed is preferable because of its higher ionic concentration. When the ultrafiltration permeate has been concentrated by a factor of four by reverse osmosis, the electrical conductivity increases by a factor of about two [100, 101]. Low conductivity is not wholly related to ionic concentration because the presence of lactose also depresses solution conductivity. Moreover, concentrated whey streams have a high protein concentration in the feed and this leads to a higher potential for protein-caused membrane fouling. A pH close to the protein isolectric point gives a better demineralization rate. The conversion of calcium salts to their ionized form by acidification and deacidification increases the conductivity of the solution. If calcium ions are replaced by sodium ions in the electrodialysis stack of deproteinated whey, the demineralization rate increases. The mobility of calcium ion is about 20% higher than the mobility of sodium ion [102, 103]; however, calcium ions have a tendency to form complexes with proteins and other species and these complexes tend to foul the membranes. The demineralization rate of whey in a good electrodialysis system is proportional to the conductivity to the power 0.95 [58, 102, 104]. Temperature also controls the demineralization of whey. For instance, batch-mode electrodialysis of ultrafiltration permeate from casein whey to a 90% demineralization product requires different times at different feed temperatures. At 20 °C, 90% demineralization takes 12 min, at 30 °C it takes 8 min and at 40 °C, only 6 min [8, 41, 104, 105]. In whey demineralization by electrodialysis, the ion removal rate follows first-order kinetics for times up to 10–20 min. After that period, the curve of demineralization rate versus time flattens. For whey demineralization by electrodialysis, the power requirement is 0.5 kWh lb^{-1} of dried whey. The current efficiency of such systems is about 60–90% depending on the system-cleaning procedures [41, 99].

Demineralization of skim milk by electrodialysis reduces the level of ash and increases the calcium/phosphate ratio in skim milk powder. Electrodialysis demineralization of skim milk increases the stability of frozen skim milk and concentrated skim milk proteins [8, 36, 41, 99, 103]. For instance, the removal of about 40% of calcium ions by electrodialysis increases the shelf life of protein stored at −8 °C from 1 to 17 weeks. A 70% calcium removal increases shelf life to 53 weeks [64, 100, 102, 104, 106–108]. Whey-protein concentrates are sometimes mixed with lactose (but not fat milk solids) to produce infant formula. It has been suggested that the commercial value of whey permeate can be increased by fermentation to lactic acid. The fermentation is carried out with a mixed culture of *Lactobacillus helveticus* and *Streptococcus thermophilus* [36, 38, 47, 99, 109–111]. This fermentation exhibits product inhibition; therefore, it is desirable to extract the lactic acid continuously as it is produced. Continuous lactic-acid production from whey permeates is done in a three-unit process comprised of the bioreactor, ultrafiltration module, and electrodialysis cell. The ultrafiltration module recycles all or part of the biomass back into the bioreactor and removes low molecular weight metabolites such as sodium lactate, which is a fermentation inhibitor. The sodium lactate solution is then extracted and concentrated continuously in an electrodialysis subsystem. The fermentation product without an electrodialysis subsystem yields an acid concentration of 40 g l^{-1}

[52, 72, 90, 94, 112–115]. Adding an electrodialysis unit increases the final lactate solution concentration to 130 $g\,l^{-1}$ [73, 94, 96, 116–118]. Electrodialysis after ultrafiltration can extract 90% of the lactic acid from the fermentation bioreactor product. Sodium hydroxide is produced during the concentration of acid by electrodialysis [37, 43, 47, 94, 96]. However, continuous lactic-acid production has some potential disadvantages. Clogging of the ultrafiltration subsystem membranes with protein deposits results in a drastic restriction of permeate flow. In addition, the elimination of cationic ions from the fermentation broth changes the pH of the broth. For maximum bioreactor production, the fermentation is usually carried out at an optimum pH, which is usually significantly higher than the pK_a of the acid being formed.

An example of fermentation and lactic acid production in the dairy industry using bipolar membrane electrodialysis is shown in Figure 4.7 (process drawing based Nordahl *et al.*, 1998). A sterilized medium such as whey permeate is mixed with protein-hydrolysing enzymes and the resultant mixture is then pumped to a continuous fermenter containing a mixture of *Lactobacillus helveticus* and *Streptococcus thermophilus*. Lactic acid is then produced in the fermenter. The fermentation product is ultrafiltered and the retentate contains the bacterial culture and nonhydrolysed whey protein. Dissolved ions pass through the membrane and concentrate the lactic acid in the permeate. An adjustment of pH with ammonium hydroxide is necessary to neutralize the acid produced. There are two different approaches to purify lactic acid from the permeate solution.

The first approach for purifying lactic acid from permeate solution was proposed by Norddahl *et al*. in 1998 [90]. Permeate from the ultrafiltration process is passed

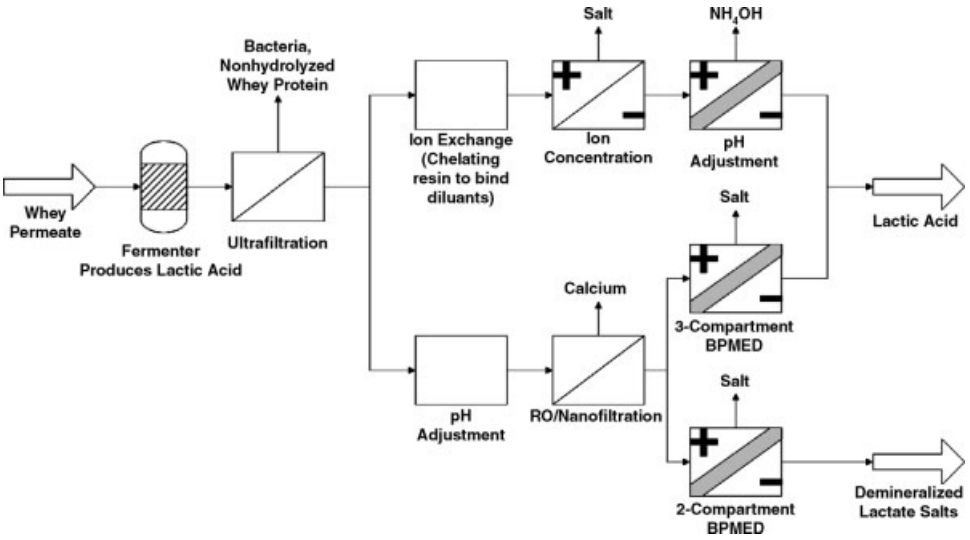


Figure 4.7 Lactic-acid production using bipolar membrane electrodialysis, adapted from Norddahl *et al.* [113].

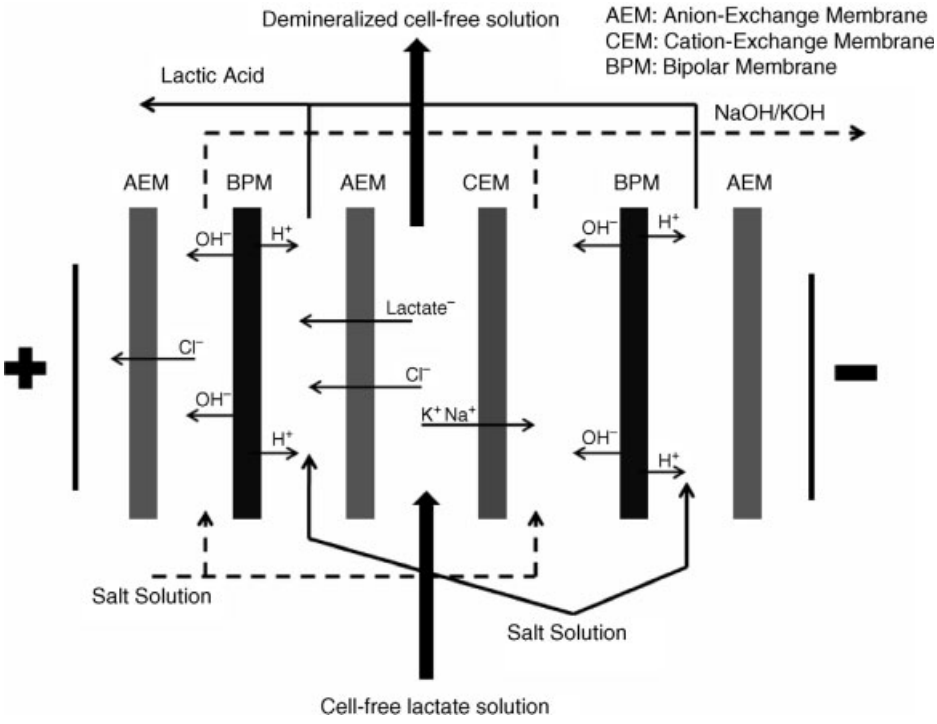


Figure 4.8 Lactic-acid purification.

through an ion chelating ion-exchange resin to remove divalent ions. This prevents irreversible precipitation of calcium salts on the surface of the membranes in later electrodialysis processes. The eluant from the ion-exchange process then is concentrated with a two-step electrodialysis. Conventional electrodialysis is used in the first step to concentrate the salt solution. Bipolar membrane electrodialysis is used in the second step to convert the salts into lactic acid, inorganic acids, and ammonium hydroxide. Lactic acid and ammonium hydroxide are recovered in two different streams using three-compartment bipolar electrodialysis as shown in Figure 4.8.

The fermentation broth is pumped through a feed compartment composed of cationic and anionic membranes. The bipolar membranes adjacent to the cathode and anode generate OH^- and H^+ groups, respectively. The lactate ions migrate toward the anode through the anion-exchange membrane and emerge into the product stream. Cations (such as ammonium, potassium, and sodium ions) migrate toward the cathode through the cation-exchange membrane, react with OH^- groups to form bases, and are removed from the stacks in the alkali stream. The overall recovery rate of lactic acid is about 85–90%, depending on the amount of sugar added to the fermenter [11, 47, 103, 119, 120]. Finally, the lactic acid is further purified or concentrated to the desired concentration using a falling-film multistage vacuum evaporator or compression evaporator.

The second approach proposed for purifying lactic acid via electrodialysis is shown by the Norddahl group in 2001 [113]. The fermentation liquid is ultrafiltered and then acidified as shown in Figure 4.7. If the pH is above 3.8, it is usually lowered to 2.5–3.0, which is lower than the pK_a value of lactic acid (3.86). The resultant free lactate ions bind with hydrogen ions to form lactic acid, having no net electrical charge. The low pH solution is then sent to nanofiltration or reverse osmosis to retain calcium and magnesium ions and molecules of molecular weight larger than 180. The calcium- and magnesium-free permeate is then treated by three-compartment bipolar membrane electrodialysis. The bipolar membrane configuration for lactate separation can also be a two-compartment configuration where either cationic or anionic membranes are omitted; these possible configurations are shown in Figures 4.9a and b, respectively.

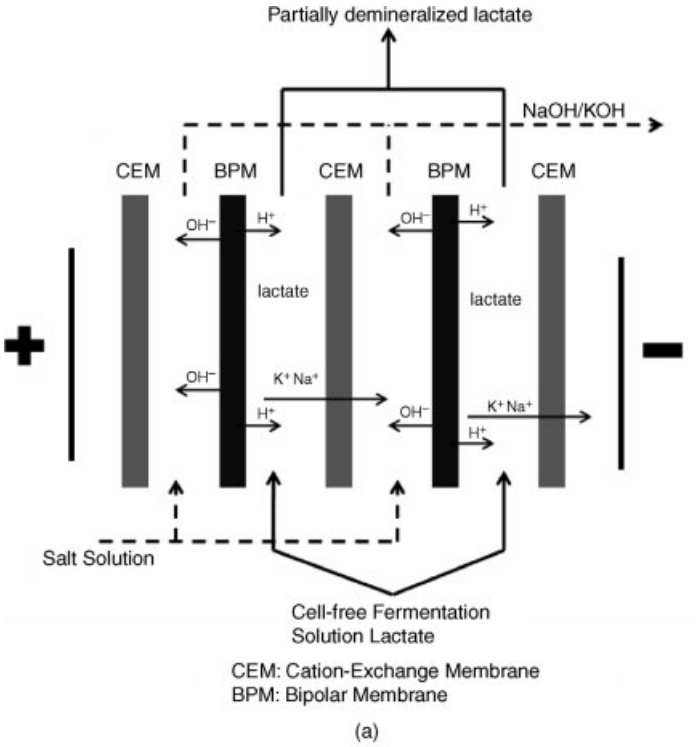
In the two-compartment systems, only cations or anions are removed from the feed compartment and replaced with either protons or hydroxide ions. There is no concentrate stream in this mode. However, two-compartment bipolar membrane electrodialysis only partially deionizes the feed, since only cations or anions are removed. Bipolar membrane electrodialysis is simple and inexpensive as compared with other methods. Bipolar membrane electrodialysis systems boast lactic acid recovery rates as 90–98% based on the amount of sugar added to the fermenter [36, 43, 47, 96, 119]. The advantages of electrodialysis process in lactic acid production over conventional lactic acid production are:

1) no chemicals are needed to regenerate ion-exchange materials;
2) the system has a higher operating efficiency;
3) the system is easier to control;
4) all of the effluent or deplete streams are recycled;
5) acids and bases are generated from optional bipolar membrane electrodialysis;
6) the concentrate from nanofiltration, the only waste stream containing only calcium/magnesium ions and color compounds, is greatly reduced.

Bipolar membrane electrodialysis can also adjust the pH of dairy products. The dairy solution is circulated on the cationic side of the bipolar membrane where H^+ ions are generated to lower the pH of the solution. Similarly, the solution is circulated on the anionic side of the bipolar membrane where OH^- ions are generated to increase the pH. The recommended current density is between 20–200 $A\,m^{-2}$, depending on the product to be treated [43, 59, 96, 98, 103, 115, 121–126]. This pH adjustment process simplifies production technology, reduces cost, and eliminates the risk of explosion [59, 102, 104, 118, 121, 123, 127–133].

Recently, bipolar membrane electrodialysis has been applied to the purification of dairy wastewaters using a three-stage process (Figure 4.10).

In the first stage, the wastewater is pretreated with a base to adjust the pH from 7 to 10. The base treatment partially precipitates the Ca^{2+}, Mg^{2+}, and PO_4^{3-} ions that are present [36, 37, 67, 96, 108, 124]. In the second stage of the process, the pretreatment wastewater is then fed to a fermentation process where the lactose and other sugars present are converted to lactic acid using the bacteria *Lactobacillus helveticus* and *Streptococcus thermophilus*. A cell recycle stream circulates a stream from the fermenter through the microfiltration unit and back into the fermenter. In the third stage, the permeate from the microfiltration is fed to the electrodialysis



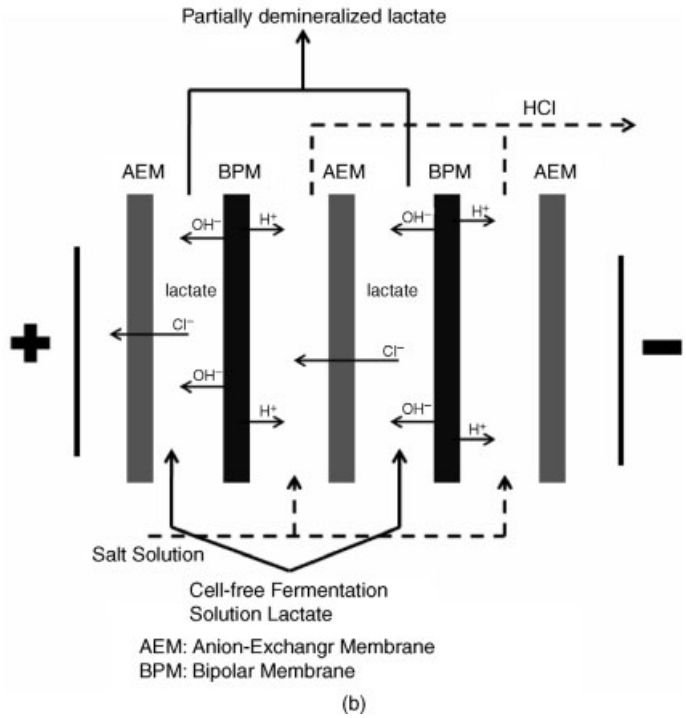


Figure 4.9 Lactate purification (a) two- and (b) three-compartment configuration.

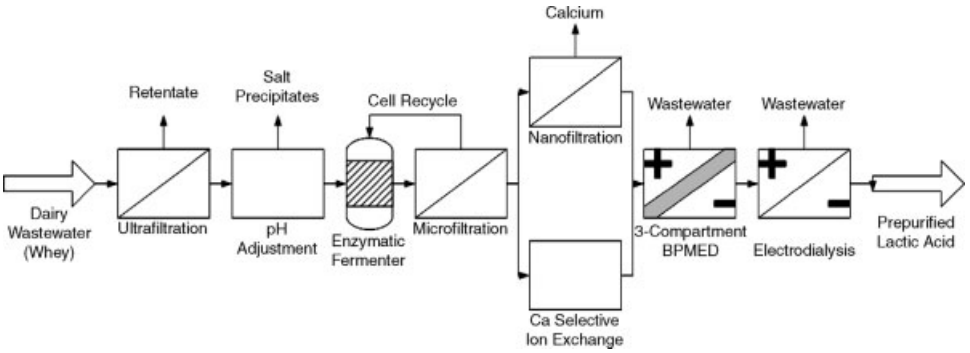


Figure 4.10 Purification of dairy wastewater, adapted from Boergardts *et al.* [114] (data in Boergardts *et al.*).

system through either a nanofiltration unit or a selective ion exchanger to remove any residual ions. In the final stage, the concentration of lactic acid in the wastewater is reduced. The produced wastewater exhibits a low chemical oxygen demand (COD) load. Bipolar membrane electrodialysis allows the isolation of free acid in high concentration, and by-product alkali is utilized to elevate the pH in the pretreatment stage. The bipolar membrane electrodialysis process in wastewater treatment is shown in Figure 4.10. The fermentation broth passes through the diluate compartment. The pH in each of the two end compartments is controlled by a bipolar membrane. The lactic acid is removed from the feed stream by the anion-exchange membrane, while the alkali ions are removed through the cation-exchange membrane. In order to achieve both high lactic acid concentration and low COD concentration [55, 114], Boergardts *et al.* suggest that concentration of fermentation broth is needed to lower wastewater concentration. During the electrodialysis step, water is circulated through the membrane stack and the products (lactic acid and alkali) are removed from the system continuously at constant concentration. Boergardts *et al.* [114] also suggest that the electrodialysis process can be carried out by a two-stage process. The fermentation broth is pumped through the first stage of bipolar membrane electrodialysis, where the broth is continuously diluted to an ionic concentration of about 10–15 $g\,l^{-1}$. In the second stage, a conventional electrodialysis system is used to further reduce the concentration of ions in the wastewater stream. The sodium lactate from the second electrodialysis stage can be recycled to the first electrodialysis stage to increase the feed concentration of lactate as shown in Figure 4.10. Results show that the COD concentration is reduced by 85–95%, the free lactic concentration is about 200 g/l, and the alkali solution concentration is about 2 $mol\,l^{-1}$ [11, 35, 36, 44, 47, 98, 99, 119].

4.3.4
Protein Fractions

The protein fraction recovery process is similar to whey demineralization and is based on the two primary characteristics of electrodialysis: decreasing the ionic

concentration (desalting) and increasing the ionic concentration (salting-out effect). These two characteristics are used in numerous applications to remove impurities that are insoluble in high or low ionic strength or in the selective removal of proteins of interest. One the first protein fraction technologies was developed in 1982 for the separation of enriched β-lactoglobulin (β-lg) and α-lactalbumin (α-la) fractions from whey [72]. Ultrafiltration is used to concentrate the whey proteins and to partially remove water, salts, lactose, and other low molecular weight compounds. The permeate from ultrafiltration is adjusted to a pH of 4.65 with either HCl or NaOH [95]. The following electrodialysis demineralization step removes low molecular ions such as sodium, potassium, calcium, and magnesium. The demineralized concentrate is readjusted to a pH of 4.65 if necessary either with 0.1 N HCl or NaOH. β-lg precipitates in this step [37, 94, 96] and the precipitate is separated from the solution by centrifugation. Using this method, the protein solutions are desalted with minimal loss of solute. About 33% of the acid whey proteins are recovered by using pH adjustment coupled with electrodialysis.

In 1995, Stack *et al.* [134] developed a new process using thermal treatment coupled with the previously described protein separation methods. Stack's process was based on an earlier process developed by Pearce *et al.* [121], a well-known process based on the thermal separation of whey proteins. In the Pearce process, the raw material is treated to reduce its specific gravity and ionic strength to levels less than 25% of the original values. Next, α-la is aggregated for 30 s by heating the whey to 55–70 °C. The flocculated α-la is recovered by centrifugation, whereas the soluble β-lg remains in the whey solution with other constituents. Stack *et al.* extended this concept to develop an efficient integrated process for treating whey and recover its constituents, especially pure β-lg fraction, the enriched α-la fraction, and lactose, as shown in Figure 4.11. In the first step, the whey is treated to reduce its mineral content using electrodialysis to achieve 70% demineralization. The cation exchange resin column removes the rest of potassium, sodium, magnesium, and particularly calcium. The treated whey is then subjected to a heat treatment at between 71 and 98 °C for 50–95 s.

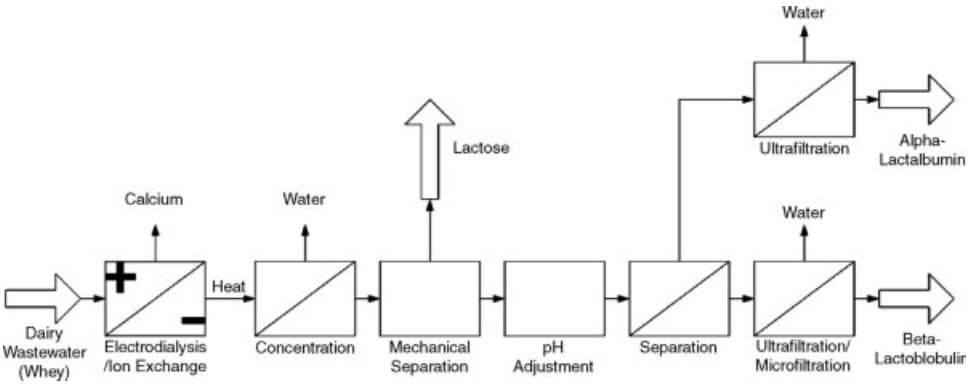


Figure 4.11 Recovery of proteins from whey, adapted from Stack *et al.* [134] (data in Stack *et al.*).

At this temperature and these ionic conditions, the β-lg remains soluble in the solution. After the heat treatment, the proteins in whey are rather soluble. The whey is then concentrated by a two-stage process to between 55–63% and the lactose crystallizes as the concentrated solution cools. In the second stage, the pH of the whey solution is adjusted to between 4.3 and 4.7 at a temperature less than 10 °C and is then heated to 35–54 °C for 1–3 h. The α-la component of the solution flocculates. Stack *et al.* [134] did not report the yield of either β-lg or α-lac proteins in whey fractions.

Combined with cation-exchange membranes, bipolar membrane electrodialysis can lower the pH of the solution in the compartment next to cationic side of the bipolar membrane. Bazinet and coworkers [41, 47, 98, 135] also fractionated whey proteins with bipolar membrane electrodialysis. As the whey solution circulates through the cells, the pH of the solution is lowered from 6.9 to 4.6. A Feed of 5% protein concentration, processed with the bipolar membrane electrodialysis system, produced a 98% pure β-lg fraction with a 44% recovery. A feed of 10% protein concentration is optimum for the bipolar membrane electrodialysis system, and a 95.3% pure β-lg fraction at 53.4% recovery can be achieved at that feed concentration. The β-lg-enriched fraction contains 2.7% of α-la for 98% total protein purity [120]. The performance of bipolar membrane electrodialysis is improved as the initial concentration of protein increases. However, if the initial concentration is above 10%, the conductivity of the solution becomes a limiting factor.

Conventional electrodialysis and bipolar membrane electrodialysis show advantages in protein fractionation compared to conventional heat-treatment methods. The electrodialysis systems give rapid and controlled recovery of salts without diluting the product. The very low molecular weight protein and peptides can be easily demineralized. The electrodialysis processes for protein fractionation are well suited for recycling the salts responsible for the salting-out effect. Both electrodialysis and bipolar membrane electrodialysis can concentrate salts in one stream, while desalting the other stream.

4.4 Hybrid Technologies

4.4.1 Electrodeionization

Based on the concepts of both electrodialysis and ion exchange resin columns, electrodeionization is the membrane process in which cation and anion exchange resins are packed between the two membranes in the feed compartment to enhance the transport of ions across the system (Figure 4.12). Electrodeionization has been widely used for ultrapure water production because it requires less energy than electrodialysis systems at low ionic concentration [9, 52]. However, electrodeionization has disadvantages that must be overcome. Since the system contains ion-exchange resins rather than a spacer between the two membranes, system leakage

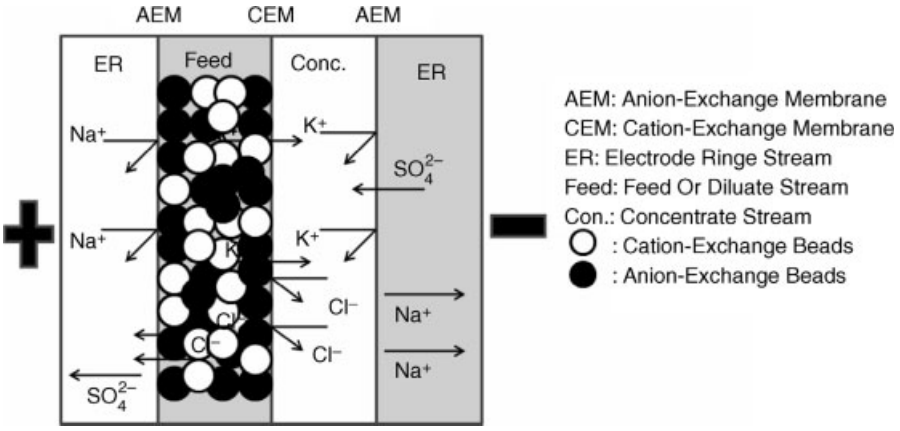


Figure 4.12 Electrodeionization.

can be severe, which greatly reduces system performance. Moreover, electrodeionization systems often exhibit uneven flow distribution due to flow channels created by the resins packed between the two membranes. These two disadvantages drive the cost for high-performance electrodeionization systems to the point that application of the technology is currently limited to ultrapure water production. Arora *et al.* [136] developed a method to bind the resins together to form a wafer that was suitable for the recovery of lactic acid. The wafer contains not only the properties of the ion-exchange resins, but also the function of the spacer; therefore, wafer-enhanced-electrodeionization technology has the potential to lower system costs. Moreover, with lower power costs for the separation of ions at low concentrations, wafer-enhanced-electrodeionization could separate low conductivity solutions found in food processing, such as milk and juice.

4.4.2 Electrochemical Coagulation

Water electrolysis, the formation of a boundary layer at the electrode/solution interface, and a convection-diffusion phenomenon are basic concepts for electrochemical coagulation (Figure 4.13) [11, 35, 135]. The pH increase in the anode compartment and decrease in the catholic compartment are results of decreased ion transport across the membrane. When a membrane separates the compartments, there is an increase in the acidity or alkalinity with respect to the bulk solution while, without the membrane, the increase in acidity and alkalinity only happens at the boundary layers formed at the electrode/solution interfaces.

Because acid and base are created at the anode and cathode, respectively, the rinse solutions in these two compartments can be used for juice and dairy treatment. For instance, the low-pH solution generated from the anode can be used as the treatment solution for precipitating whey protein, especially α-lactalbumin. Another application is to use the cathode rinse to clean the membranes and the electrodialysis stack.

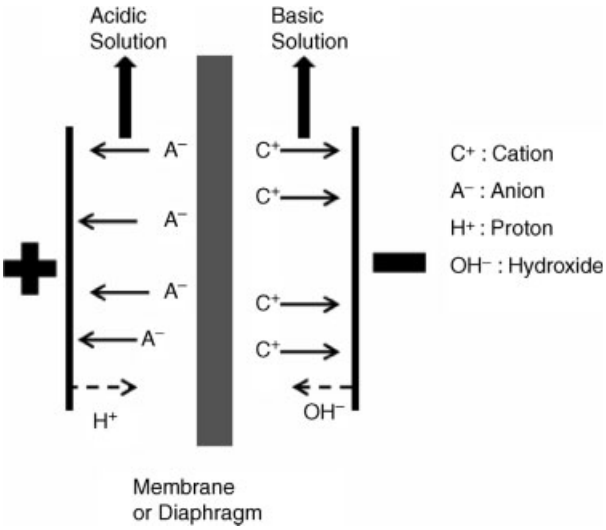


Figure 4.13 Electrochemical coagulation.

The high-pH solution from the cathode chamber can be used to balance the acidity of juices such as pineapple, orange, or grape [135].

4.4.3 Electroreduction

The use of electric voltage to break covalent bonds, thereby forming new molecules, is the basic concept of electroreduction technology. The covalent bond is broken by the electrical field, while the solution is circulating in the cathode compartment of the electrodialysis stack [11, 35, 94]. A new bond is formed when the solution moves out of the compartment, as shown in Figure 4.14. The breaking of divalent bonds, especially disulfide bonds in proteins, has been applied widely in protein analysis of biological species. This same phenomenon could be applied to protein separations in the dairy industry. By using electric potential, the disulfide bonds of α-la and β-lg can be broken, and new chains of proteins with different side chains can be formed so that proteins of higher purity can be recovered. Using electroreduction, the production of free sulfhydryl (SH) groups and prevention of the thiol-disulfide interchange reaction increases the stability of proteins.

4.5 Conclusion and Future Innovations

Many applications of electrodialysis are found throughout the food industry. The electrodialysis techniques used include conventional electrodialysis,

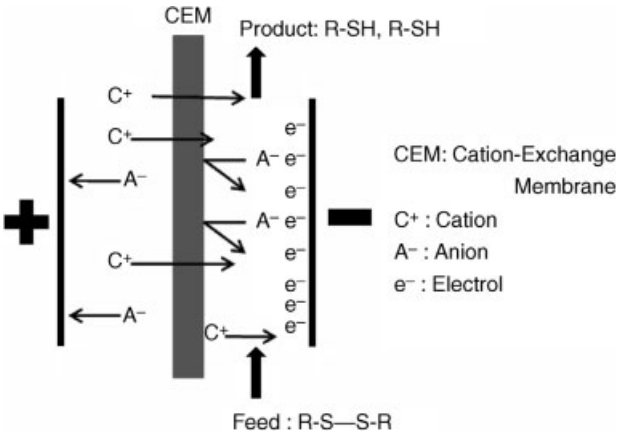


Figure 4.14 Electroreduction.

three-compartment electrodialysis, bipolar membrane electrodialysis, and other hybrid technologies. However, the commercial use of electrodialysis techniques is still limited to niche applications such as juice deacidification or whey-protein demineralization. This nonacceptance is attributed to the fact that the mechanisms of electrolytic phenomena are very complex, especially for multicomponent systems. The lack of a detailed understanding of oxido-reduction in electrolytic phenomena and redox reactions of food compounds limits the broad application of electrodialysis and the electrolytic cell. Electrodialysis and electrolytic cell techniques have the potential to improve and integrate into more food processes. Possible candidate applications include the selective removal of ions, waste recovery, and others awaiting exploration.

Although electrodialysis has matured during the past several decades, its application in the food industry is still limited. The food industries are typically late adopters of new technology as compared to other industries such as the chemical or pharmaceutical industries. Some factors that have prevented electrodialysis from wide acceptance in the food industries are membrane fouling, limited cleanability, and poor membrane chemistry. For food applications, membrane fouling is a severe problem that decreases the system performance and increases the cost per amount of product. As addressed earlier, electrodialysis membranes are typically cleaned by the system vendor rather than though *in-situ* cleaning. This makes the technology inconvenient and costly. In electrodialysis, ion removal is usually nonselective, which limits the applicability of electrodialysis for specific ion removal. These factors provide many opportunities for electrodialysis research. Innovation of new membrane chemistry designed for low fouling and high selectivity in ionic removal would expand the use of electrodialysis. Moreover, innovative system design leading to easier installation and in-situ cleaning is a key requirement for the expansion of the use of electrodialysis for food–related applications. For more information on electrodialysis purchase, a vendor list is given in Appendix 4.A.

Appendix 4.A: Electrodialysis Vendor List

Company name	Location	Contact information
Alpine Technical Services, Inc.	Utah, USA	www.alpinetech.US
Ameridia	New Jersey, USA	www.ameridia.com
Applied Membranes, Inc.	California, USA	760-727-3711
Applied Water Solutions, Inc.	Massachusetts, USA	www.appliedwatersolutions.com
Baymont Technologies, Inc.	Texas, USA	281-260-0667
CelTech, Inc.	North Carolina, USA	www.celtechinc.com
ChemTreat, Inc.	Virginia, USA	www.chemtreat.com
Crane Environmental	Pennsylvania, USA	732-202-9211
Eden Purification Systems	Connecticut, USA	www.edenpurificationsystem.com
Eurodia Industrie	New Jersey, USA	www.eurodia.com
Exergy Tecnologies Corp.	California, USA	949-679-3990
GE Water and Process Technologies	Pennsylvnia, USA	www.gewater.com
Ion Power, Inc.	Delaware, USA	www.ion-power.com
Jinan Haochua Industry Co., Ltd.	Shandong, China	www.jnhaohua.com
Koch Membrane Systems, Inc	Massachusetts, USA	978-657-5208
Minntech Corporation	Minnesota, USA	www.mintech.com
Sparkling Clear Industries	Texas, USA	www.sparklingclear.com
TTS Technologies	Tampere, Finland	358-3-31422011

Nomenclature

C	Ion concentration
c^-	Concentration of anions
c^+	Concentration of cations
E	Energy consumption
F	Faraday constant
I	Electric current
k	Equilibrium constant
Q	Flow rates
t^-	Transport number for anions
t^+	Transport number for cations
u	Velocity of cations
v	Velocity of anions
V	Voltage potential applied across the stack
Z	Valence of ions

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