Downstreaming of Lactic Acid from Hydrolysate of Rye after Fermentation

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ABSTRACT

Various methods of separation were studied for the production of lactic acid after fermentation of glucose from hydrolysate of shredded rye. The fermentation broth successively passed through ultrafiltration, softening, conventional electrodialysis that operated in a two-level mode (water transport: 0.42 L/eq; current efficiency: 63%), three-compartment electrodialysis with bipolar membranes (water transport: 0.19 L/eq; current efficiency: 75%), ion exchange, decolourisation, and finally evaporation. The product of the pilot plant was a concentrated lactic acid with a small portion of impurities and a concentration of up to 750 g/L. This process can be used to clean lactic acid for high-grade applications in industry.

Keywords: Lactic acid, Downstreaming, Ultrafiltration, Electrodialysis, Ion exchange resin

1. INTRODUCTION

The final product is won by downstreaming after fermentation by the application of different process steps such as ultrafiltration, ion exchange, electrodialysis with mono-polar and bipolar membranes, as well as evaporation. The number of downstreaming steps strongly influences the quality and the price of the product. Thus the total costs are determined mainly by the downstreaming rather than by production of the product using fermentation (Aljundi et al., 2005). Lactic acid is an organic acid with a wide area of applications (Vick Roy, 1985; Van Velthuijsen, 1994). The application of lactic acid from renewable raw materials plays an ever stronger role in the production of biodegradable polymers (Datta et al., 1995; Vaidya et al., 2005). High purity requirements are made of the product for the production of poly-lactic acid. Therefore gentle product treatment and cost-effective technologies that are attractive in terms of energy and safety engineering as well as being environmentally sound are necessary, for instance membrane filtration and electrodialysis (Paul and Ohlrogge, 1998; Reimann, 2005a). The separation of inorganic salts and proteins represents a special problem with the production of valuable substances from renewable raw materials, so that the methods used for downstream processing will play a very important role (Thang et al., 2005a, 2005b). Desalination, purification and concentration of sodium lactate after fermentation are possible by conventional electrodialysis (EDM) (Nolasco-Hipolito et al., 2001; Bazinet, 2004; Fidaleo and Moresi, 2004; Wee et al., 2005) and the concentrated lactate can be converted into lactic acid and cleaned further by means of water-splitting electrodialysis (EDB) with bipolar membranes (Persson et al., 2001; Habova et al., 2004a, 2004b). However, a pre-treatment of the fermentation broth is required to separate biomass (ultrafiltration) and to remove

multivalent cations (ion exchange) before applying the electrodialysis (Bailly, 2002). An overview of past and new developments of recovery of lactic acid from fermentation broth is given by Wasewar (2005).

In this paper the investigations concentrate on the down-stream processes of lactic acid in the form of sodium lactate made by fermentation of the renewable raw material rye. Glucose used for the fermentation was obtained by hydrolysis of shredded rye and contains a high proportion of inorganic salts and organic compounds. The down-stream processes took place at the operations presented in an earlier paper (Reimann, 2005b) for downstreaming of sodium lactate produced by fermentation of glucose from hydrolysate of shredded barley.

2. MATERIAL AND METHODS

2.1 Membrane Filtration

The membrane filtration studies were carried out in a pilot plant of Messrs. UFI-TEC GmbH Oranienburg (Germany) with exchangeable modules and membranes as shown in Figure 1.

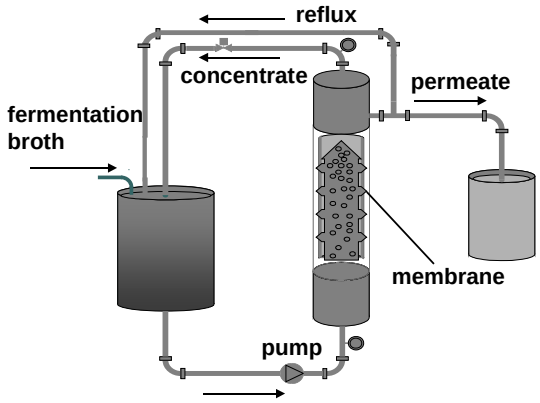


Figure 1. Test equipment for membrane filtration.

The temperature was kept between 32 and 35° C by using a heat exchanger. In the tubular module used, a ceramic tubular membrane with a membrane effective filtration area of 0.2 m² was applied. The characteristic values of the *INSIDE* CeRAM UF membrane (TAMI Germany GmbH) examined are:

- Material: $Al_2O_3/TiO_2/ZrO_2$,
- Cut-off: 50 kD
- Number of channels: 8,
- Tube diameter: 25 mm,
- Tube length: 1200 mm,
- Filter area: 0.2 m².

Samples were drawn according to a predetermined schedule for analysis of different ingredients. The temperature and pressure in front and behind the membrane, as well as the permeate flow were recorded regularly during the experiments.

2.2 Removal of Divalent Cations

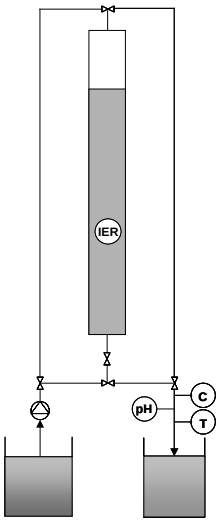
The set-up of the laboratory-scale ion exchange unit (IE unit) is shown in Figure 2. The column from UIT Umwelt- und Ingenieurtechnik GmbH Dresden, Germany, was 1290 mm high with an inside diameter of 80 mm. The bed volume (BV) of the resin was 6 L. Chelating resin RCH 46 (Eurodia Industrie SA, Pfullingen, Germany) was used to remove multivalent metal ions from clarified fermentation broth before the electrodialysis experiments. On the basis of the producer's specification, the following separation and regeneration procedure was applied:

Separation

1. Down-flow: 7.2 bed volumes of sodium lactate solution. Flow rate: 36 L/hr.

Regeneration

1. Down-flow: rinsing with 6 bed volumes of de-ionised water. Flow rate: 36 L/hr.
2. Up-flow: rinsing with 4 bed volumes of de-ionised water. Flow rate: 48 L/hr.
3. Down-flow: regeneration with 3 bed volumes of HCl (50 g/L). Flow rate: 36 L/hr.
4. Down-flow: slow rinsing with 4 bed volumes of de-ionised water. Flow rate: 24 L/hr.
5. Down-flow: fast rinsing with 4 bed volumes of de-ionised water. Flow rate: 48 L/hr.
6. Up-flow: regeneration with 2 bed volumes of NaOH (50 g/L). Flow rate: 24 L/hr.
7. Up-flow: slow rinsing with 4 bed volumes of de-ionised water. Flow rate: 24 L/hr.
8. Down-flow: fast rinsing with 4 bed volumes of de-ionised water. Flow rate: 48 L/hr.



IER: Ion exchange resin, C: Conductivity,
pH: pH-Value, T: Temperature

Figure 2. Set-up of a laboratory scale ion exchange unit.

Samples were drawn from the original solution at the beginning of a run, in accordance with a predetermined schedule, and at the end of a run for analysis of lactic acid and ions of Ca and Mg.

2.3 Electrodialysis (ED)

The electrodialysis experiments for mono-polar and bipolar electrodialysis were conducted using a laboratory facility with 4 cycles (Fig. 3) and the membrane stack OS-ED-100 Quadro (OSMOTA Membrantechnik GmbH Rutesheim, Germany). The membranes AMX/CMX were used for the mono-polar electrodialysis, and the mono-polar membranes AMX/CMX as well as the bipolar membranes of Neosepta, Tokuyama Corp., Japan, for the bipolar electrodialysis. The size of the cell frame was 15 x 15 cm with a thickness of 0.5 mm. The effective membrane area was 100 cm². The number of membranes used comprised 10 AMX, 11 CMX and 10 bipolar membranes. Each circuit was equipped with a pump and measuring devices for flow, pressure, temperature, pH-value and conductivity. Conductivity, pH and temperature were measured with a MultiLine P3pH/LF (WTW Weilheim, Germany). The power supply to the membrane stack was provided via a direct current supply unit (EA-PS 7065 – 10 A, EA Elektro-Automatik GmbH Viersen, Germany) with a controllable voltage from 0 to 50 V and current from 0 to 10 A, designed for running with constant current and constant voltage.

The experiments were carried out in a batch mode. Four storage tanks (each 10 L) were used to hold dilute (salt), concentrated (acid), base, and electrode rinse solutions. The stock tanks were temperature-managed by thermostat to maintain the temperature between 33 and 36° C. In all stack configurations, the electrode rinse solution was re-circulated continuously to transfer the electric current and to remove gases produced by the electrode reaction during the operation of the ED. From each chamber, 10 cm³ samples were taken according to a predetermined schedule for analysis of lactic acid, inorganic and organic materials.

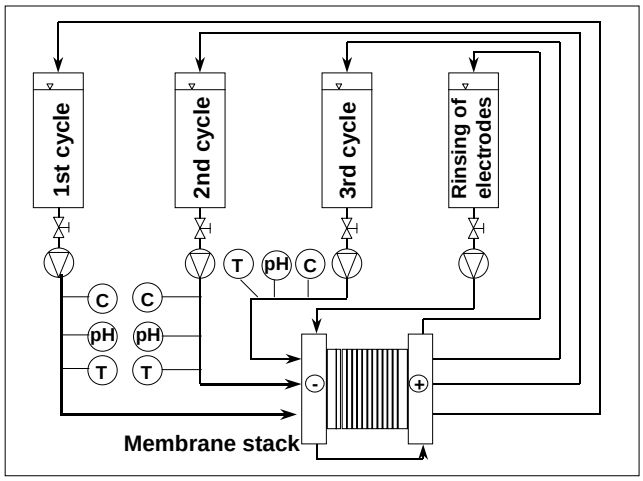


Figure 3. Apparatus for electrodialysis experiments.

2.3.1 Mono-polar Electrodialysis (EDM)

The principle is illustrated in Figure 4. The electrode rinse solution (Na_2SO_4 – 5 g/L), the concentrate (sodium lactate – initial concentration 1.3 g/L) and the diluate (sodium lactate – initial concentration 81.3 g/L) were circulated through the corresponding chambers of the stack with the flow rates in the three channels ranging from 2.5 to 3.0 L/min for each chamber. For the period of constant current 3 A was applied. The experiments were finished

when the conductivity in the diluate dropped to 2 - 10 mS/cm (concentration of sodium lactate 17 to 18 g/L).

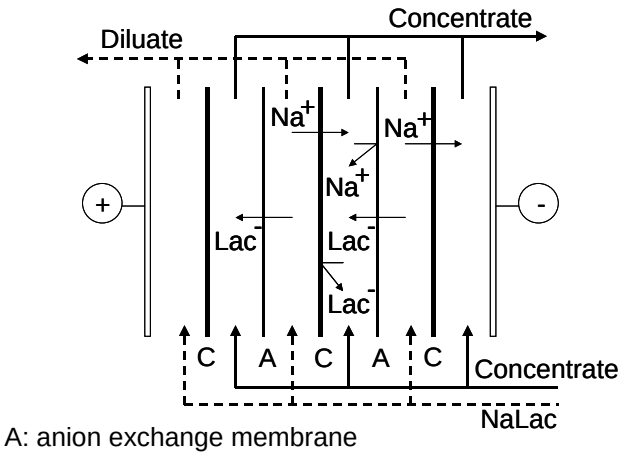


Figure 4. The process scheme of mono-polar electrodialysis.

2.3.2 Bipolar Electrodialysis (EDB)

The following solutions were used for the EDB: NaOH – 9.5 g/L (electrode rinse solution), NaOH – 12.6 g/L (base stream), lactic acid – 1.2 g/L (acid stream). A current density of 500 A/m² was applied. The circulation flow rates in the channels ranged from 2.5 to 3.0 L/min. The experiments were carried out in three-compartment bipolar electrodialysis.

The three-compartment bipolar electrodialysis unit (EDB**)** consisted of ten cell pairs with bipolar membranes, anion exchange membranes and cation exchange membranes, and four solution tanks (salt stream, acid stream, base stream, and electrode rinse solution). Bipolar membranes, anion exchange membranes, and cation exchange membranes were arranged alternately. During ED operation lactate ions and sodium ions in the salt compartment moved simultaneously into the acid and base compartments through anion and cation exchange membranes, respectively. Free lactic acid was formed by combination of lactate ions and hydrogen ions generated on the cation exchange layer of the bipolar membrane, while sodium hydroxide was generated simultaneously by combination of sodium ions and hydroxyl ions on the anion exchange side of the bipolar membrane (Fig. 5).

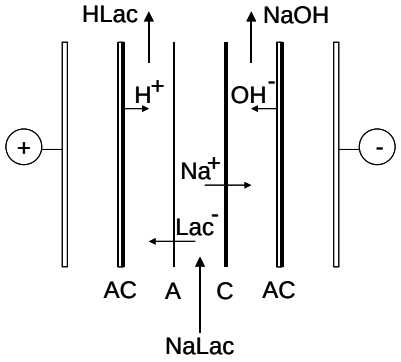


Figure 5. The process scheme of the three-compartment bipolar electrodialysis.

2.4 Ion Exchange

Ion exchange (IE) is a fixed-bed separation technology using ion exchange resins (Helferich, 1959). These resins have a high number of firmly attached bonds on their surfaces, which can adsorb anions and cations reversibly. The capacity of exchangeable ions is limited, however. The quantity of ions that can be separated by given quantities of resins is determined experimentally. The same applies with regard to the required amount of rinsing water and regenerant, which removes the adsorbed ions and thus regenerates the resin to its previous state. The set-up of the laboratory-scale ion exchange unit was the same as shown already in Figure 2.

For the exchange of cations the same column was used as for the removal of divalent cations (section 2.2). The bed volume (BV) of the resin Relite EXC08 (strongly acidic resin) from Residion S.R.L. Mitsubishi Chemical Corporation, Italy was 4.5 L. For the exchange of anions the column from QVF Labortechnik Ilmenau, Germany, was 1750 mm high with an inner diameter of 22 mm. The bed volume (BV) of the resin Relite EXA133 (weakly basic resin) from Residion S.R.L. Mitsubishi Chemical Corporation, Italy was 0.4 L. Decolourisation was carried out in the same column as was used for the exchange of anions. The bed volume (BV) of the renewable Hypersol-Macronet resin Relite MN500 from PUROLITE GmbH Ratingen, Germany, was 0.4 L. The flow rate of the lactic acid through the column was 2 BV/hr.

2.5 Analytical Methods

Lactic acid and glucose concentrations were measured by HPLC using a GYNKOTEK chromatograph, Germany (column: Eurokat H (KNAUER); 300 x 7.8 mm I.D.; eluent: 0.003 n H_2SO_4; flow rate: 0.8 mL/min; sample volume: 50 µL; temperature: 25° C; pressure: 3 MPa; detection: RI). The concentration of sodium lactate was calculated from the concentration of lactic acid. Water content of biological dry solid matter (BTS) was determined gravimetrically after drying at 105° C. Total Kjeldahl nitrogen (TKN) was analysed using standard-method Vapodest apparatus from Gerhardt by digestion using a selenium catalyst. The colorimetric technique was used to measure total phosphorus (TP) with the molybdenum blue method. Anions and cations were determined under the following conditions using the ion chromatograph DX-120 from Dionex, Idstein: column: IonPac AS14 (4 mm) with precolumn (anions); Ion-Pac CS12A (4 mm) with precolumn (cations); eluent: 3.5 mM disodium carbonate, 1 mM sodium hydrogen carbonate (anions), 22 mM sulfuric acid (cations)**;** flow rate: 1.12 mL/min (anions), 1.1 mL/min (cations); detection: conductivity with auto-suppression; suppressor: ASRS in the recycle mode (anions), CSRS in the recycle mode (cations); injection volume 25 µL; elution duration: 12 min (anions), 14 min (cations). Concentrations of Ca ions and Mg ions were determined by AAS (Vario 6, analytikjena, Germany). The colour intensity of the solutions was measured by spectrophotometer at the wavelength of 420 nm relative to water.

3. RESULTS AND DISCUSSION

3.1 Ultrafiltration

The components of sodium lactate solution after fermentation are set out in Table 1.

Table 1. Components of sodium lactate solution after fermentation

Components	Unit	Value
Sodium lactate	(mg/L)	92 100
Glucose	(mg/L)	0
Biological dry solid matter BTS	(mg/L)	9100
TKN	(mg/L)	1190
TP	(mg/L)	276
Na^+	(mg/L)	23 800
K^+	(mg/L)	1170
Ca^{2+}	(mg/L)	35
Mg^{2+}	(mg/L)	89
NH_4^+	(mg/L)	76
Cl^-	(mg/L)	496
PO_4^{3-}	(mg/L)	243
SO_4^{2-}	(mg/L)	1196
NO_2^-	(mg/L)	< 5
NO_3^-	(mg/L)	6
pH	-	6.65
Conductivity	(mS/cm)	41.8
Extinction	(420 nm)	0.88

The fermentation broth from the lactic acid fermentation was filtered to remove the cells in order to prevent deposition of bacteria on the membrane surface and the creation of bacteria clusters in the space between the membranes of the electrodialysis unit. All cells of the fermentation broth were removed and cell-free permeate was obtained by ultrafiltration (UF).

Owing to deposition of organic and inorganic substances on the membrane surface and in its pores (fouling and scaling), permeate flux of UF-membrane decreased gradually within the operation time (Fig. 6). By rejection of biomass the concentrations of different compounds are changed, as shown in Table 2. Sodium lactate was able to pass through the membrane completely.

The quality of the solutions was based on the rejection of components. Pollution rejection ® was quantified by decreasing concentrations, either total or soluble, defined by Equation (1):

$$R = [1 - (c_p / c_f)] * 100 \quad (\%) \quad (1)$$

where c_p is the concentration of the cleaned solution and c_f is the feed concentration at a given time.

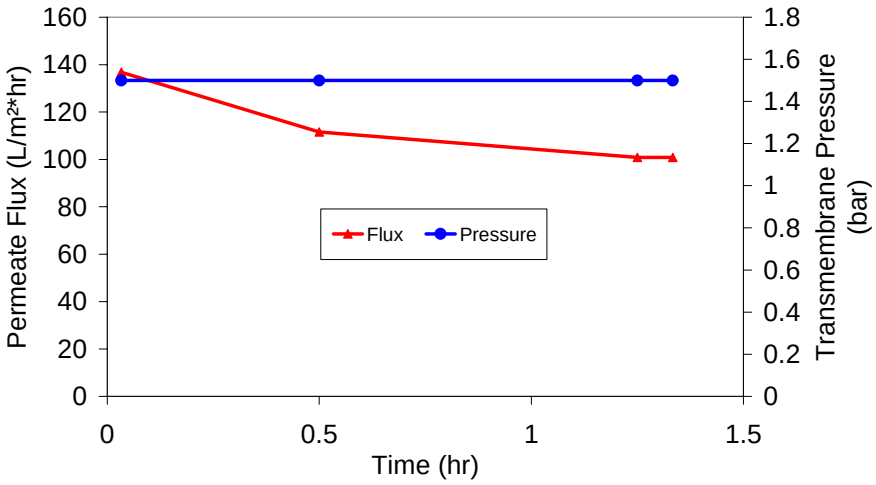


Figure 6. The time course of permeate flux and transmembrane pressure for ultrafiltration of sodium lactate after fermentation using ceramic tubular membrane (cut-off: 50 kD).

Table 2. Composition of initial and treated fermentation broth by ultrafiltration

Compound	Initial fermentation broth	Treated fermentation broth	Rejection R (%)
Sodium lactate (mg/L)	92 100	92 100	0
BTS (mg/L)	9100	0	100
TKN (mg/L)	1190	740	38
TP (mg/L)	276	229	17

3.2 Removal of Multivalent Metal Ions

Multivalent metal ions (Ca, Mg etc.) have to be removed from the cell-free fermentation broth. Their concentration must be altogether lower than 1 mg/L. According to the specification of the chelating resin RCH 46, the total exchange capacity of 1 L resin corresponds to 1 equivalent cation of heavy metals. The capacity of this resin is dependent upon the pH (alkaline pH for Mg and Ca). It is recommended that laboratory trials (column tests) be carried out to prove the process. Since the resin used was new, after preliminary tests the process was designed with 20% of the determined capacity.

These data and concentrations of Ca and Mg ions in the solution of sodium lactate resulted in a capacity of 108 L solution/bed volume BV resin. The solution was separated at a flow rate of 6 BV/hr. The loss of sodium lactate was 11.7%. The rejection for Ca and Mg ions was 98.6% and 99.9%, respectively (Table 3).

Table 3. Composition of initial and treated sodium lactate solution using chelating resin RCH 46

Compound	Cell free fermentation broth	Treated fermentation broth	Rejection R (%)
Sodium lactate (mg/L)	92 100	81 300	11.7
Ca^{2+} (mg/L)	35	0.5	98.6
Mg^{2+} (mg/L)	82	0.1	99.9

It is possible to control the procedure by measuring the conductivity and the pH-value of the solution after passing the column (Fig. 7).

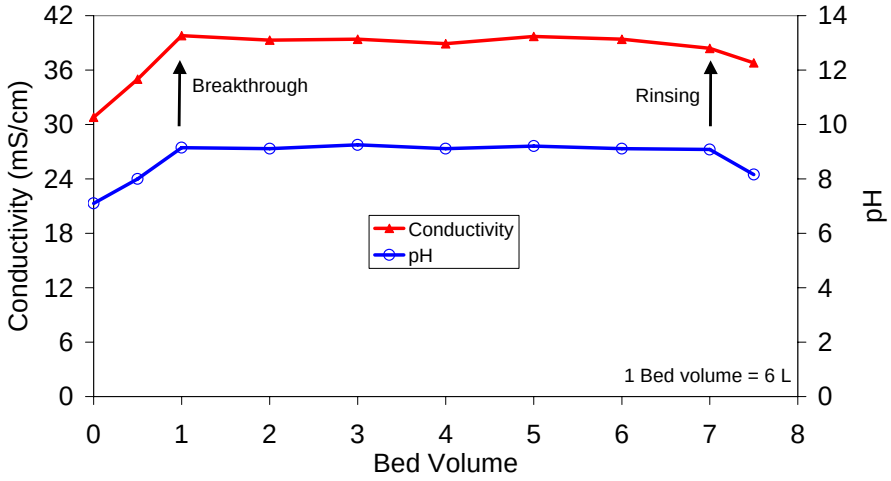


Figure 7. Conductivity and pH-value plotted as a function of throughput volumes of sodium lactate solution measured in units of bed volumes using chelating resin RCH 46.

The breakthrough of dissolved sodium lactate and starting point of rinsing are marked with an arrow. The sudden increase in conductivity marks the breakthrough and the beginning of ion exchange. Finally, the solution displaced by the rinsing solution in the column is diluted with a part of the bed volume of the rinsing solution. As a result, the concentration of sodium lactate in the solution decreases from 92.1 g/L to 81.3 g/L after processing through the column.

3.3 Conventional Electrodialysis

The product sodium lactate is concentrated and purified by conventional ED. The value of the concentration is a very important factor for the subsequent lactic acid recovery step of electro-conversion. The degree of concentration (the ratio of the final concentration in the concentrate to the initial diluate concentration) can be influenced by the ratio of the initial diluate volume to the initial concentrate volume. For the trials the degree of concentration was limited by a minimal value of 1 L in the concentrate. The electrodialysis was therefore operated in two-level mode.

The results of the experiments using electrodialysis are presented as current efficiency, CE (%), and specific energy consumption, SEC (kWhr/kg). The current efficiency CE was calculated using the equation:

$$CE = t_{th} / t_{exp} = [((NaL_{in} - NaL_{fin}) / EW) * F / (I * CP * t_{exp})] * 100 \quad (\%) \quad (2)$$

where t_{th} is the theoretical and t_{exp} the experimental time, NaL_{in} and NaL_{fin} represent, respectively, the initial and final amount of sodium lactate in the feed reservoir (i.e. the diluted feed), EW is the equivalent weight of sodium lactate, F is Faraday constant, I is the current (A), and CP the cell pairs in the stack.

The specific energy consumption, SEC, was calculated using the equation:

$$SEC = \int_{0}^{t_{fin}} (U * I) * dt / (NaL_{in} - NaL_{fin}) \qquad (kWhr/kg) \qquad (3)$$

where U is the voltage (V), I is the current (A), and t the run duration time (hr). Since U and I can change during a run (depending on the power supply conditions), the integral in Equation 3 has to be evaluated numerically on the basis of experimental data.

Figure 8 shows the time course of the conductivity in the diluate and concentrate circuit as well as the power required to transport ions and the load of lactic acid for a constant current period of 3 A for the two-level electrodialysis with the sodium lactate solution. Performance parameters for two-level electrodialysis are listed in Table 4 and show that an increase of sodium lactate in the concentrate by two-level electrodialysis does affect water transport (the volume of water passed to the equivalent of the transported sodium lactate), current efficiency and specific energy consumption.

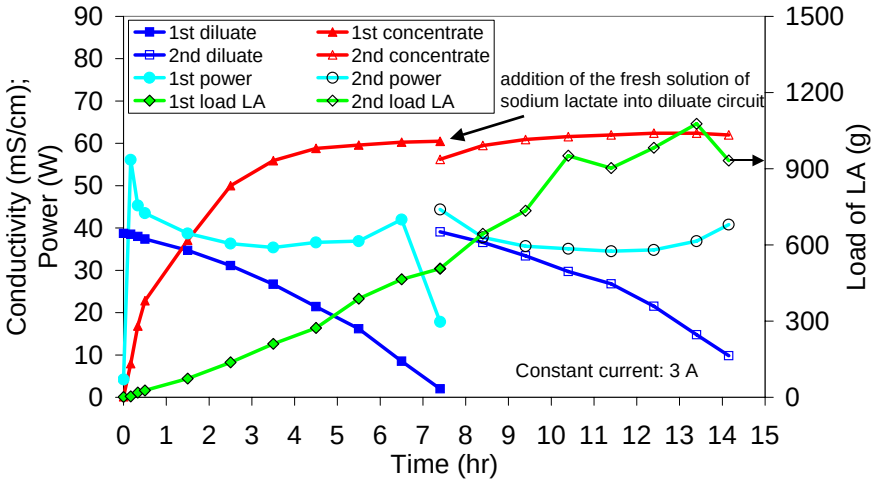


Figure 8. Evolution of conductivity, power and load of lactic acid (LA) in the diluate and concentrate circuit vs. time during the two-level concentration of solution of sodium lactate by conventional electrodialysis.

Table 4. Parameter during two-level conventional electrodialysis of sodium lactate solution

Parameter	Stage of experiment	
	1st stage	2nd stage
Operating time (hr)	7.4	6.75
Voltage (V)	15.1	12.5
Current density (A/m²)	291	300
Initial volume of diluate (L)	8.5	8.5
Initial volume of concentrate (L)	1	2.872
Initial concentration of diluate (g/L)	81.3	81.3
Final concentration of diluate (g/L)	16.9	17.6
Initial concentration of concentrate (g/L)	1.3	219.5
Final concentration of concentrate (g/L)	219.5	239.2
Water transport (L/eq)	0.33	0.42
Current efficiency (%)	74	63
Specific energy consumption (kWhr/kg)	0.54	0.58

Since only charged particles are transported in the electric field during the electrodialysis, purification was carried out for the concentrate solution of uncharged particles. This led to uncharged compounds of nitrogen remaining in the diluate solution (Table 5).

Table 5. Concentrations of selected ingredients in the diluate and concentrate solution after two-level conventional electrodialysis of sodium lactate solution

Compound	Diluate solution	Concentrate solution	Rejection (%)
Sodium lactate (mg/L)	81 300	239 200	-
TKN (mg/L)	670	273	59
TP (mg/L)	208	197	5

3.4 Bipolar Electrodialysis

The bipolar electrodialysis was investigated using a three-compartment membrane stack configuration. The membrane stack consisted of anion exchange, cation exchange and bipolar membranes to allow three streams to flow, i.e. acid, base, and salt streams.

The experiment was carried out in a constant current mode (5 A). Figure 9 shows the time course of the EDB. The experiment had to be interrupted after a time of 2 hours and a further 3 hours and 20 minutes and was continued in each case on the following day. The trial was stopped at an electrical conductivity of 4 mS/cm in the salt solution. Experimental results are summarised in Table 6. A final lactic acid concentration of about 179 g/L, corresponding to 87% conversion, was obtained. The specific energy consumption for the recovery of 1 kg of lactic acid was 1 kWhr and the current efficiency was 75%.

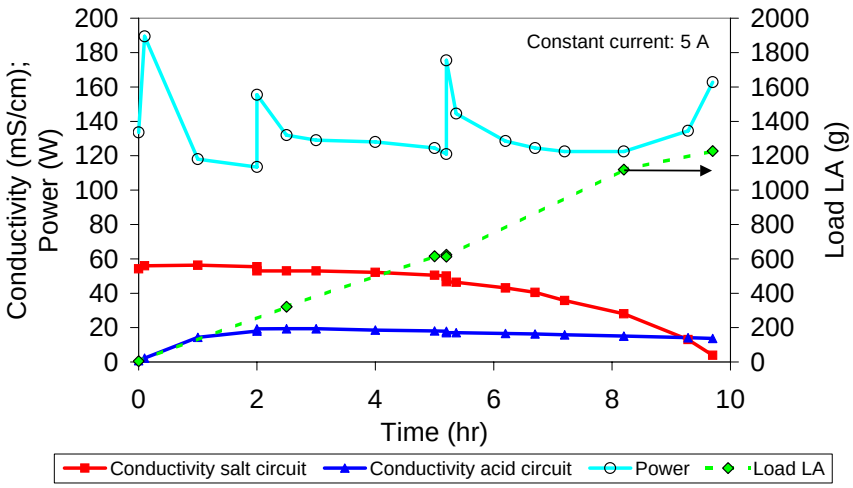


Figure 9. Evolution of conductivity in the salt and acid circuit as well as of power and load of lactic acid (LA) vs. time during three-compartment bipolar electrodialysis of solution of sodium lactate.

Table 6. Parameter during the three-compartment bipolar electrodialysis (EDB) of sodium lactate solution

Parameter	Three-compartment EDB
Operating time (hr)	9.7
Average voltage (V)	28.5
Current density (A/m²)	500
Initial volume of NaL (L)	7.3
Initial volume of HLac (L)	4.27
Initial volume of NaOH (L)	5.15
Initial concentration of NaL (g/L)	239.2
Final concentration of NaL (g/L)	6.14
Initial concentration of HLac (g/L)	1.22
Final concentration of HLac (g/L)	178.5
Initial concentration of NaOH (g/L)	12.6
Rate of conversion (%)	87
Water transport (L/eq)	0.19
Current efficiency (%)	75
Specific energy consumption (kWhr/kg)	1

With three-compartment electrodialysis a purity of the lactic acid is obtained for cations and uncharged particles (Table 7).

Table 7. Concentrations of selected ingredients in the sodium lactate solution and in the lactic acid solution after three-compartment bipolar electrodialysis (EDB)

Compound	Sodium lactate solution (mg/L)	Lactic acid solution (mg/L)	Rejection (%)
TKN	273	120	56
TP	197	180	9
K^+	2200	15	99
NH_4^+	43	7	84
Cl^-	1100	1020	7

3.5 Final Purification Stages and Evaporation

Impurities of inorganic and organic compounds, which still remain in the concentrated lactic acid after both electrodialysis steps (mono-polar and bipolar), were almost completely eliminated by cation and anion exchange resins. The course of the conductivity and pH-value dependence on the throughput volumes is shown in Figure 10. The start and the end of the ion exchange ("Breakthrough" and "Rinsing" in Figure 10) are indicated, in each case, by a change of conductivity and pH-value.

For decolourisation of the lactic it is also possible to control the procedure by measuring the conductivity and the pH-value of the solution after passing the column (Fig. 11).

The results listed in Table 8 were achieved after concentration of the purified lactic acid by vacuum evaporation.

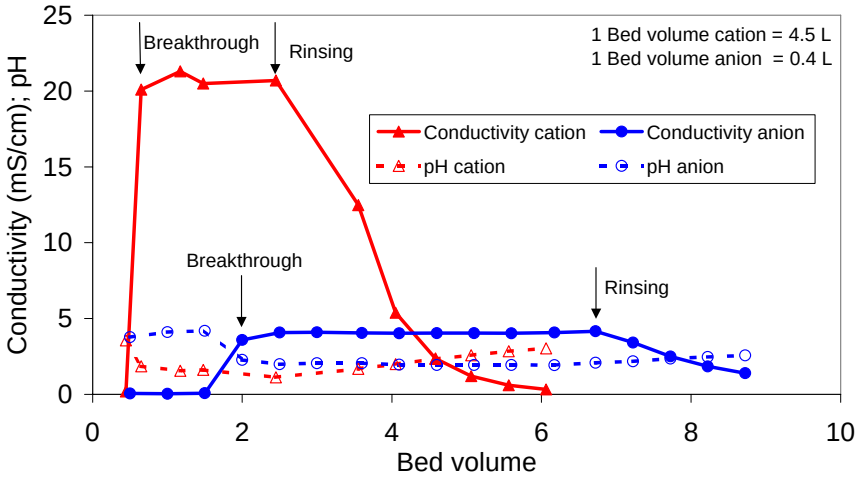


Figure 10. Conductivity and pH-value plotted as a function of throughput volumes of lactic acid measured in units of bed volumes by the up-flow desalting step for the anion (EXA133) and cation (EXC08) exchange.

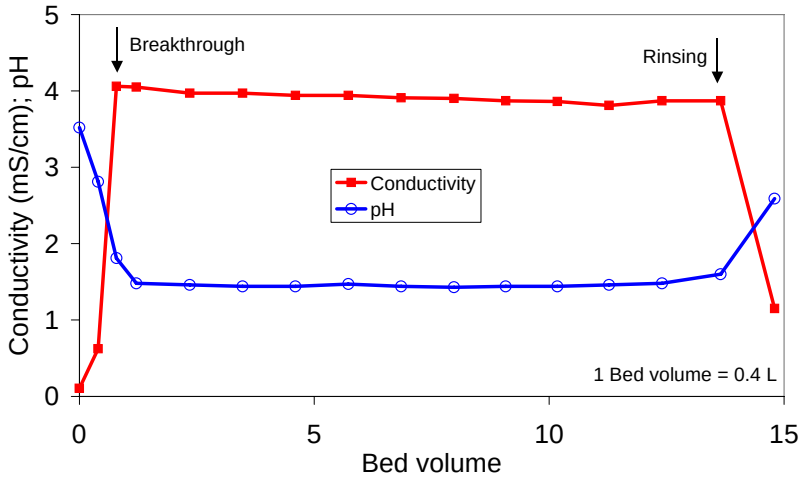


Figure 11. Conductivity and pH-value plotted as a function of throughput volumes of lactic acid measured in units of bed volumes by the up-flow decolourisation (MN500).

Table 8. Concentrations of selected ingredients in the lactic acid solution before and after desalting by cation and anion exchange resin, decolourisation as well as concentration by evaporation

Compound	Initial concentration	Final concentration	Rejection (%)
HLac (mg/L)	178 500	750 000	-
Na^+ (mg/L)	220	14	94
K^+ (mg/L)	15	2.13	86
Ca^{2+} (mg/L)	0.4	0.7	-
Mg^{2+} (mg/L)	0.2	0.18	10
NH_4^+ (mg/L)	7	0.41	94
Cl^- (mg/L)	1020	217	79
PO_4^{3-} (mg/L)	310	20	94

TKN (mg/L)	120	218	-
TP (mg/L)	180	n.d.	-
pH	1.4	2.63	-
Conductivity (mS/cm)	17.4	0.35	-
Extinction (420 nm)	0.034	0.004	-

4. CONCLUSIONS

Lactic acid separation after fermentation of glucose from hydrolysate of shredded rye was studied comprehensively and the results obtained showed very good agreement with the literature sources (Bailly, 2002; Reimann, 2005b). The results confirm that two-stage electrodialysis is a suitable and efficient technique for recovering lactate ions from the pretreated fermentation broth and subsequent conversion into lactic acid with respect to environmental aspects. Ultrafiltration and softening of the sodium lactate solution are required in order to operate the electrodialysis properly.

In the first conventional electrodialysis step, the final sodium lactate concentration of up to 239.2 g/L was obtained, while the final lactic acid concentration of 178.5 g/L was reached in the second three-compartment bipolar electrodialysis step. The total energy required in both electrodialysis processes representing the energy consumption for the sodium lactate transfer and for its electroconversion to lactic acid was about 1.56 kWhr/kg of lactic acid obtained. Chemical impurities such as inorganic cations and compounds of nitrogen were considerably reduced. Additional de-ionisation and decolourisation process steps using ion exchange resins were integrated to polish the free lactic acid for high-grade applications in industry.

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