

Separation and Concentration of Lactate from Cassava Fermentation Broth by Reverse Osmosis

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A reverse osmosis experiment was performed to separate and concentrate lactate from cassava fermentation broth. Pure lactic acid and ammonium lactate solutions were also used as model solutions. The influence of operating conditions, including feed velocity, transmembrane pressure and feed concentration, on the filtration properties (permeate flux, rejection and osmotic pressure) were studied. The concentration factor of lactic acid during batch operation of reverse osmosis was also evaluated. In the laminar flow regime, permeate flux increased with increasing of feed velocity due to concentration polarization of the solute on the membrane surface. However, the permeate flux was not affected by feed velocity in the turbulent regime. Permeate flux and rejection increased with transmembrane pressure and decreased with feed concentration due to higher osmotic pressure. At a transmembrane pressure of 5.5 MPa and an initial feed velocity of 0.7 m/s, lactic acid in the model solutions could be concentrated from three to six times; however, the concentration factor in fermentation broth only reached two. The degree of concentration increase of lactic acid was affected by the presence of medium and residual sugar in the fermentation broth, as both may contribute to the increase of osmotic pressure and also polarize the concentration effect that occurs on the membrane surface.

Key words : lactic acid fermentation broth / reverse osmosis / concentration factor / concentration polarization / osmotic pressure

1. Introduction

Poly(lactic acid) (PLA) derived from biomass is a typical bio-plastic that can be made through three processes: fermentation, separation-concentration, and polymerization. In order to reduce the cost of PLA production, we propose an on-site specification system for an integrated PLA production process. The fermentation process involves production of lactic acid using fresh cassava roots (FCR) as a substrate, tofu liquid waste (TLW) and a concentrate of maguro waste (CMW) as the medium, and *Streptococcus bovis* as the strain¹⁻³. The polymerization process involves synthesis of PLA by direct polycondensation under vacuum without catalysts, solvents or initiators⁴. For the separation-con-

centration process, we used reverse osmosis. Compared to direct distillation, reverse osmosis requires a relatively low energy⁵ because it can be performed at low temperature and no phase change occurs during the process. The use of reverse osmosis also fulfills the conditions for compactness, as well as for safe and simple operations for on-site cell plants.

Many works have reported on the separation and concentration of lactic acid by reverse osmosis⁵⁻⁸. These researchers have studied the effect of operating conditions on filtration properties (permeate flux and rejection) using a model lactic acid solution, fermentation broth from whey permeate, or both. However, the effect of concentration polarization on filtration properties and on the concentration factor of lactic acid have not been thoroughly discussed.

In the present study, the efficiency of lactic acid separation and concentration from a fermentation cassava broth using reverse osmosis was investigated. Model solutions of lactic acid and ammonium lactate were

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used as standards. The effects of operating conditions (feed flow rate, transmembrane pressure and feed concentration) on permeate flux, rejection and osmotic pressure were studied. The concentration factor of lactic acid during batch operation at constant pressure was also reported.

2. Theory

The permeate flux (J_v) in reverse osmosis can be expressed as⁹⁾:

$$J_v = L_p (\Delta P - \sigma \Delta \pi) \quad (1)$$

$$J_s = \bar{C}_s (1 - \sigma) J_v + \omega \Delta \pi \quad (2)$$

where L_p is the permeability coefficient of water, P is the transmembrane pressure, σ is the reflectivity coefficient, π is the osmotic pressure difference across membrane, J_s is the permeate flux of solute, \bar{C}_s is the average concentration of solute and ω is the permeability of solute.

In order to solve for \bar{C}_s , the membrane is first differentiated, and Eq. (2) is then evaluated according to the concentration partition and differentiated as follows:

$$J_s = C_s (1 - \sigma) J_v - D \frac{dC_s}{dx} \quad (3)$$

where D corresponds to the diffusion coefficient.

At steady-state, J_s and J_v are constant, and the concentration of permeate (C_P) can be expressed as:

$$C_P = \frac{J_s}{J_v} \quad (4)$$

Combining Eqs. (3) and (4), Eq. (3) can be solved using the boundary conditions $x = 0$, $C_s = C_M$ (the concentration on the membrane surface), and $x = m$, $C_s = C_P$ (the permeate concentration). This results in the following correlation, termed the intrinsic rejection (R_{int}):

$$R_{int} \equiv \frac{C_M - C_P}{C_M} = \frac{\sigma (1 - F)}{(1 - \sigma F)} \quad (5)$$

$$\text{where } F = \exp \left[- \frac{J_v (1 - \sigma)}{D / \delta_m} \right] \quad (6)$$

and m is the thickness of the membrane.

As P approaches infinity, J_v also goes to infinity, and R_{int} becomes equivalent to R_{obs} . On the other hand, the observed rejection (R_{obs}) is defined by Eq. (7).

$$R_{obs} = \frac{C_F - C_P}{C_F} \quad (7)$$

At a higher feed velocity, where C_M is nearly equal to C_F (feed concentration), R_{int} is nearly equal to R_{obs} .

The osmotic pressure for an electrolyte solution is defined by the van't Hoff equation as follows:

$$\Delta \pi = i \Delta C RT \quad (8)$$

where i is the van't Hoff coefficient, C is the difference in the concentration of solute on the membrane surface (C_M) and permeate concentration (C_P), R is the universal gas constant ($8.314 \text{ Pa} \cdot \text{m}^3 \cdot \text{mol}^{-1} \cdot \text{K}^{-1}$) and T is the absolute temperature.

The relationship between the van't Hoff coefficient (i) and the degree of dissociation (α) can be expressed as follows:

$$i = 1 + (n - 1)\alpha \quad (9)$$

where n is total number of ions in one formula unit.

Permeate flux (J_v) can also be described in terms of the concentration polarization model.

$$J_v = k \ln \frac{C_M - C_P}{C_F - C_P} \quad (10)$$

$$\text{while } k = \frac{D}{\delta_b}$$

where δ_b is the thickness of the boundary layer over which the concentration gradient exists.

3. Materials and methods

The experiment was carried out using a disk-shaped plate-and-frame reverse osmosis (RO) module (LabStak M-20, DSS, Denmark) with a thin composite membrane (HR98PP, Alfa Laval, Denmark). The membrane skin layer is fully aromatic polyamide. The experimental equipment is shown in Fig. 1. The number of membranes used was between 4 and 14. The

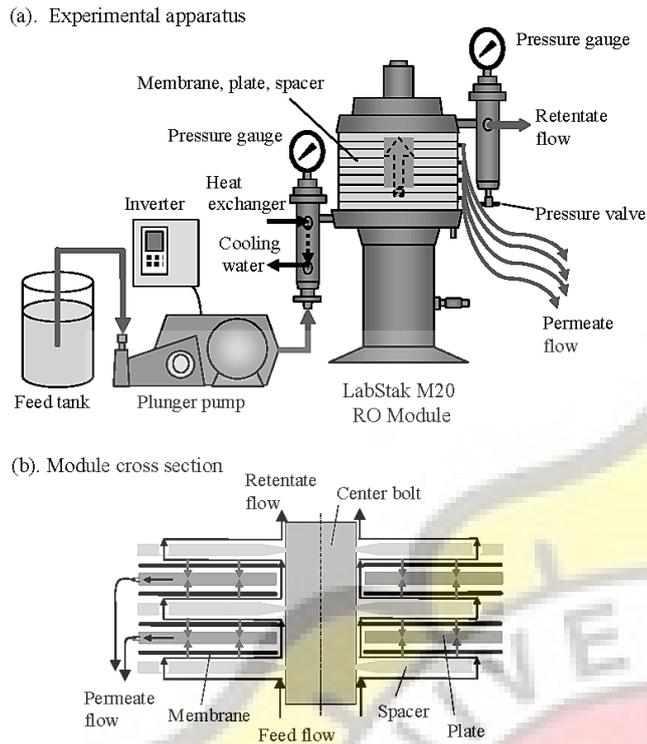


Fig. 1 Experimental apparatus for reverse osmosis (a) and module cross section (b).

membranes had an effective surface area of 0.018 m² each and the rejection of NaCl was 96%. A plunger pump (MW1051, Maruyamaexcell, Japan) was used to supply the solution to the RO membrane module. The pump operates up to pressures of 14.0 MPa.

A solution containing L-lactic acid (Wako Chemical, Japan) was used as model solution; the concentration varied from 0.15 to 0.78 mol/L. The pH of the lactic acid solution was adjusted to 5.4 by addition of NH₄OH solution in order to obtain a similar pH to that of the fermentation broth, thus resulting in an ammonium lactate (NH₄La) solution. The fermentation broth was obtained by fermenting fresh cassava roots using *Streptococcus bovis* as the strain and Trypto soya broth as the medium. The concentration of lactic acid and residual sugar were analyzed using a Biosensor BioFlow-5 (Oji Instrument, Japan).

Microfiltration of the fermentation broth was first conducted to remove bacterial cells. The reverse osmosis experiment was carried out at 25 °C while varying the transmembrane pressure from 1.0 to 5.8 MPa and the feed flow rate from 3.1 to 22.6 L/min. The average cross-flow velocity was calculated based on the average width of a permeation channel (with an average cross sectional area of 5.1 mm²) and corre-

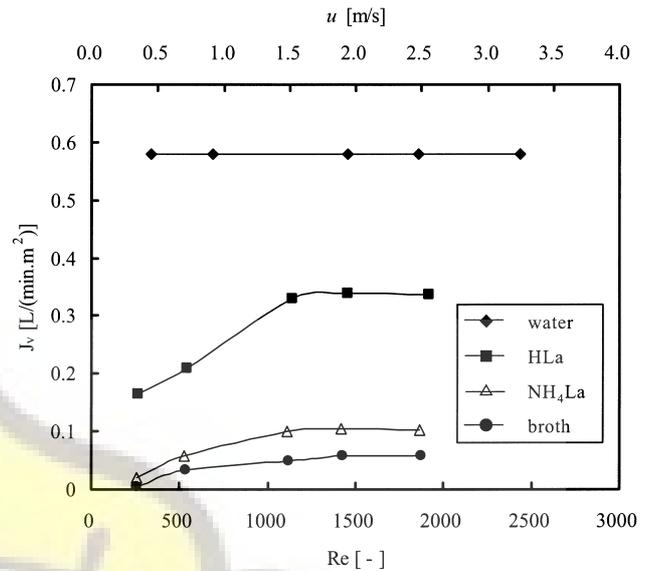


Fig. 2 Effect of the Reynolds number on permeate flux at $P = 3.2$ MPa and $C_F = 0.53$ mol/L.

sponds to a value of 0.34 ~ 2.46 m/s. The Reynolds number was evaluated based on the height of the permeation channel (0.46 mm). The calculation of the Reynolds number in the disk-shape plate and frame LabStak M20 RO module was done similarly to the previous study by Morao et al.¹⁰. The experiments were conducted using two modes. To assess separately the effect of the transmembrane pressure and feed concentration, the permeate was returned to the feed tank. For the concentration experiments (batch operation), permeate was not returned to the feed tank.

4. Results and discussion

4.1 Effect of feed velocity on permeate flux and concentration on membrane surface

Fig. 2 shows the effect of feed velocity (u) or Reynolds number (Re) on the permeate flux of water, model solutions of lactic acid (HLa) and ammonium lactate (NH₄La), and fermentation broth at a transmembrane pressure (P) of 3.2 MPa and feed concentration (C_F) of 0.53 mol/L. It can be seen that except for water, the permeate flux increased with increasing feed velocity from about 0.34 m/s ($F_f = 3.1$ L/min, $Re = 250$) to 1.5 m/s ($F_f = 13.5$ L/min, $Re = 1100$), and then the permeate flux was not affected by feed velocity at rates above 1.5 m/s. This is because concentration polarization occurs at feed velocities less than 1.5 m/s due to laminar flow in which Re was less than 1100.

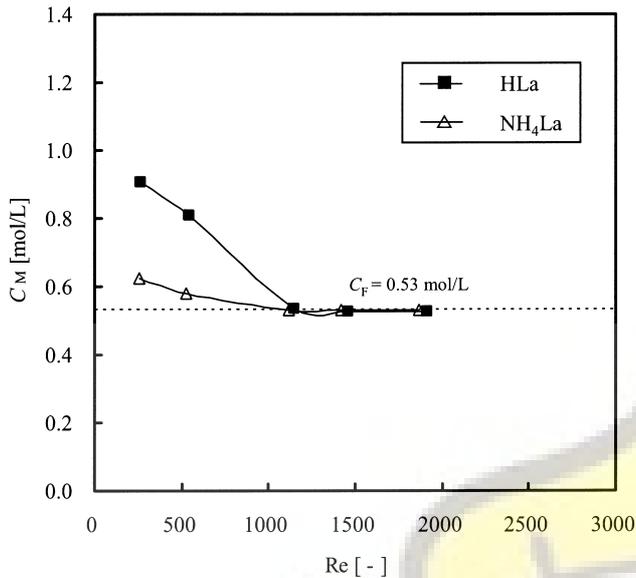


Fig. 3 Effect of the Reynolds number on concentration at the membrane surface at $P = 3.2$ MPa.

When Re was higher than 1100, turbulent flow occurred on the membrane surface because the flow duct is not smooth. This turbulence is expected to give better mixing and result in less solute buildup on the membrane surface, eliminating the effect of concentration polarization.

Schlicher and Cheryan⁵⁾ performed lactic acid separation from fermentation broth using a tubular RO module. They found that the permeate flux was not affected by the feed flow rate over the experimental range of 6 to 21 L/min. This range is equivalent to a Reynolds number (Re) of 22000 ~ 38000. Wagner et al.¹¹⁾ also reported that the permeate flux of NaCl was independent of flow rate above 3 L/min ($Re = 1500$) using a flat-sheeted RO membrane module in the turbulent flow regime.

The constant permeate fluxes for the HLa and NH_4La solutions and fermentation broths at Re higher than 1100 were found to be 0.33, 0.10 and 0.06 L/(min·m²), respectively. The osmotic pressure (π) during turbulent flow, where C_M is nearly equal to C_F , can be calculated from Eqs. (8) and (9). The dissociation degree (α) for the HLa solution was 0 at a pH of 1.8, and for NH_4La solutions was 1 at a pH of 5.4. There were two total ions ($n = 2$) in the HLa and NH_4La solutions. The van't Hoff coefficients from Eq. (9) of HLa and NH_4La solutions were found to be one and two, respectively. At higher feed velocities, the observed rejection (R_{obs}) approached R_{int} . At higher

transmembrane pressures, R_{int} converges to the reflective coefficient (σ). In the experiment conditions, the reflective coefficient (σ) nearly equals 1.0 for all solutions. This value is reasonable because the specification value of R_{obs} of NaCl solution is 0.96 for the membrane to be used. The permeability coefficients (L_p) of the HLa and NH_4La solutions were then calculated by Eq. (1) and were found to be 0.177 and 0.174 L/(min·m²·MPa), respectively. These values are nearly similar to the L_p of water (0.181 L/min·m²·MPa).

The concentration of lactate on the membrane surface (C_M) in the model solutions at laminar flow was calculated by Eqs. (1) and (8) using the permeate flux data in Fig. 2. The effect of Re on the lactate concentration on the membrane surface (C_M) of the model solutions (HLa and NH_4La) is shown in Fig. 3. It can be seen that the lactate concentration on the membrane surface decreased with increasing Re from 250 to 1100. For Re higher than 1100, the C_M was constant and equal to the feed concentration (C_F): 0.53 mol/L. This is because at higher values of Re , turbulent flow increases the shear stress on the membrane surface and leads to a decrease in the concentration polarization effect. Fig. 3 also shows that when Re is less than 1100, the C_M of the HLa solution was higher than that of the NH_4La solution. This is due to lack of solubility between HLa ($\alpha = 0$) and NH_4La ($\alpha = 1$) at pH 1.8 and 5.4, respectively.

4.2 Effect of transmembrane pressure and feed concentration on permeate flux and rejection in model solutions

Figs. 4 show the effect of the transmembrane pressure on the permeate flux (a) and observed rejection (b) of the NH_4La solution at a pH of 5.4 and feed flow rate of 6.4 L/min ($u = 0.70$ m/s, $Re = 540$) for various feed concentrations. Fig. 4a shows that permeate flux (J_p) increased with increasing transmembrane pressure (P) and decreased with increasing feed concentration (C_F), from 0.15 mol/L to 0.78 mol/L. The decrease in permeate flux with feed concentration can be attributed to the increase in osmotic pressure. The solid line shows the experimental data and the dashed line shows the theoretical calculation of permeate flux at various transmembrane pressures and the given lactate concentrations by Eq. (1). It can be seen that the experimental data of permeate flux was lower than that of theoretical ones. This is because at the laminar flow

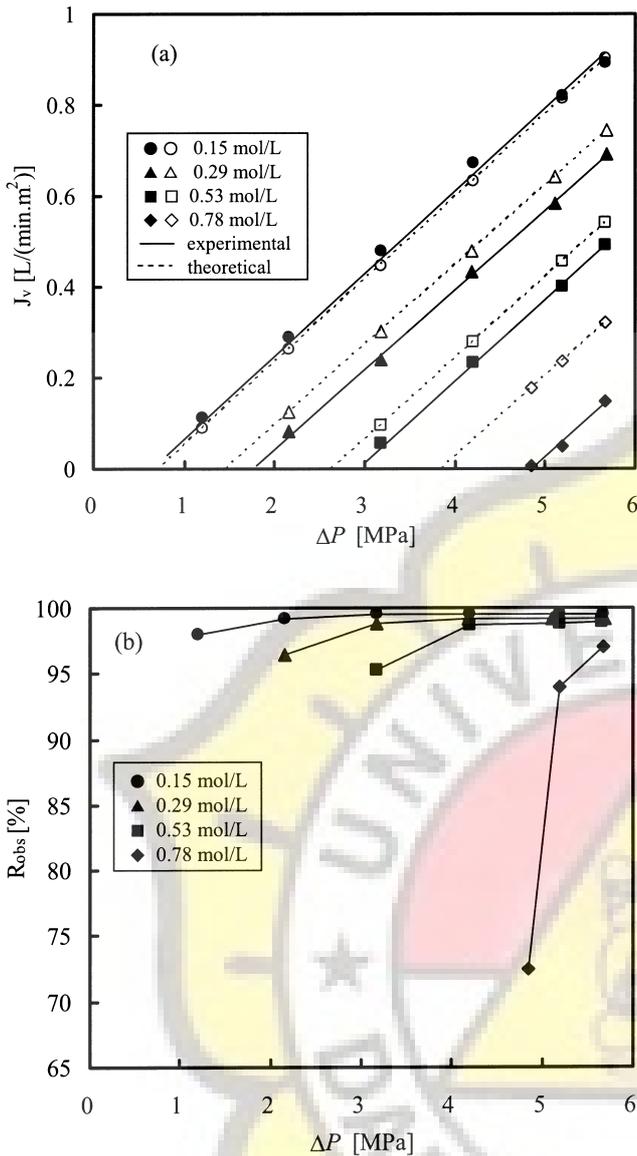


Fig. 4 Effect of the feed concentration on permeate flux (a) and rejection (b) for an NH_4La solution at a pH of 5.4 and a feed flow rate of 6.4 L/min.

regime ($Re = 540$), concentration polarization on membrane surface occurred, which led to increased osmotic pressure. The slope of $J_v - P$ plot was also found to be similar for all concentration, indicating that the permeability coefficient (L_p) was constant.

Fig. 4b shows that rejection (R_{obs}) of NH_4La slightly increased with increasing transmembrane pressure and decreased as the feed concentration increased. This result is in agreement with a study by Liew et al.⁷, in which they reported that both permeate flux and rejection of NH_4La increased with increasing transmembrane pressure (from 1 to 7 MPa). Further, the permeate flux and rejection decreased as the feed concentration increased from 0.92 to 5.8 wt% using a flat-

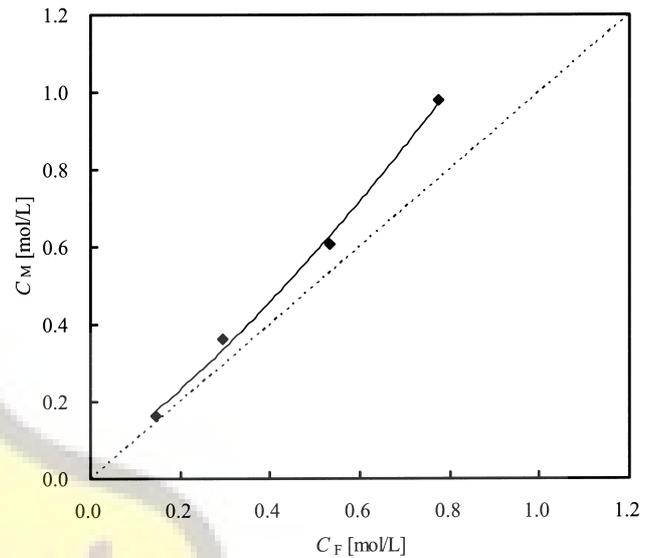


Fig. 5 Relationship between C_M and C_F for the NH_4La solution at a pH of 5.4 and feed flow rate of 6.4 L/min.

sheet composite membrane placed in a stirred cell. Ditzl et al.¹² also found that the rejection of lactic acid increased with increasing transmembrane pressure. We also found that the R_{obs} is very low at high lactate concentration and low transmembrane pressure. Gotor et al.¹³ reported similar result for reverse osmosis experiment of chloride.

In accordance with Eq. (1), the osmotic pressure can be determined when the permeate flux approaches zero, as shown in Fig. 4a. The concentration of lactate on the membrane surface (C_M) was then calculated and correlated with the osmotic pressure using Eq. (8). The relationship between C_M and C_F of the NH_4La solution is shown in Fig. 5. It can be seen that the C_M was higher than the C_F , and that the gap between the C_M and C_F increased with increasing C_F because concentration polarization occurred under laminar flow ($Re = 540$).

4.3 Permeate flux and rejection of fermentation broth

Figs. 6 show the effect of transmembrane pressure on permeate flux (a) and observed rejection (b) for fermentation broth at a pH of 5.4 and feed flow rate of 6.4 L/min ($Re = 540$). The triangle and circle symbols represent fermentation broth produced by batch operation, and the square and rhombus symbols represent the broth produced by continuous fermentation. The fermentation broth produced by the batch process contains no residual sugar; however, residual sugar was

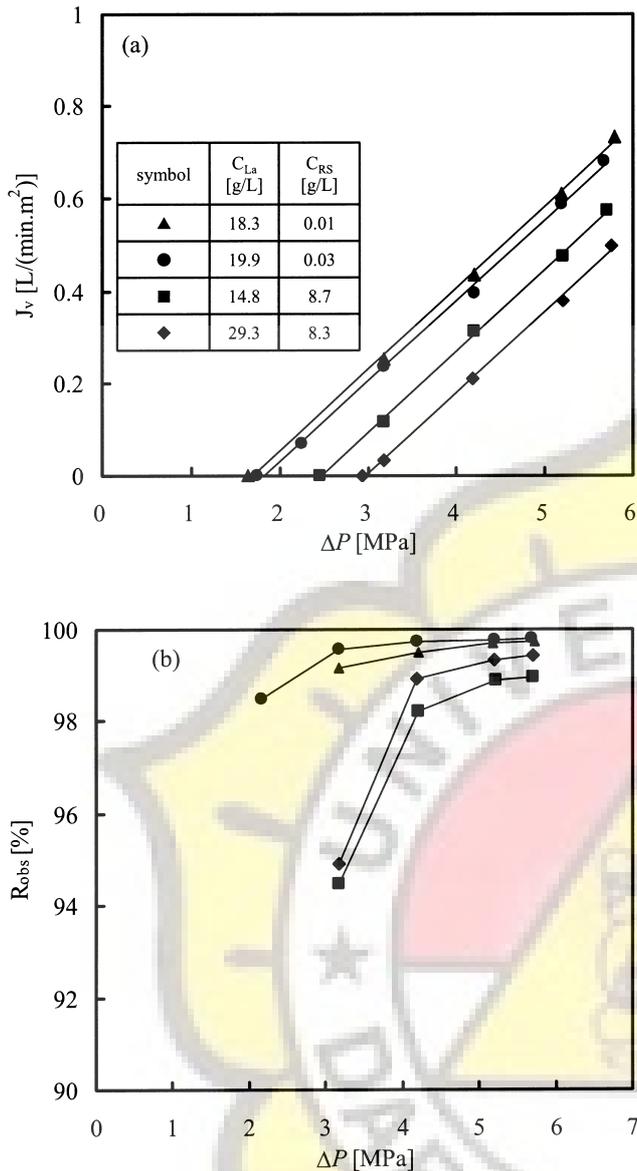


Fig. 6 Effect of transmembrane pressure on permeate flux (a) and rejection (b) for the fermentation broth and feed flow rate of 6.4 L/min.

found in small amounts in the fermentation broth produced by continuous fermentation. The difference in the amount of lactate and the concentration of residual sugar in the fermentation broths affected the permeate fluxes. As shown in Fig. 6a, the permeate flux increased linearly with increasing of transmembrane pressure for all solutions, which exhibited similar permeability coefficients, as evident from the curve gradient. The permeate flux of the fermentation broth produced by the continuous process was found to be lower than that produced by the batch process. This is presumably due to the presence of residual sugar in the former, which increased the osmotic pressure.

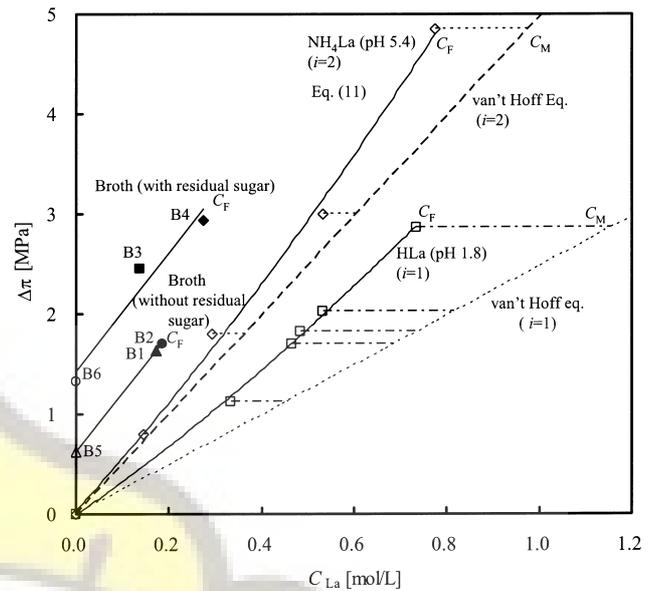


Fig. 7 Relationship between lactate concentration and osmotic pressure at a feed flow rate of 6.4 L/min.

Schlischer and Cheryan⁵⁾ also reported that the permeate flux decreased with increasing lactate concentration from 11 g/L to 44 g/L, and reported a residual sugar concentration from 6.3 g/L to 25.2 g/L in the fermentation broth of whey permeate.

The rejection of lactate (R_{obs}) slightly increased with increasing transmembrane pressure until it reached a constant value (Fig. 6b). This result is in agreement with the study by Li et al.⁶⁾, who found that lactic acid rejection increased from 92.6% to 96% as the transmembrane pressure increased from 4.1 MPa to 5.5 MPa using DS 11 AG (Osmonics) RO module.

4.4 Osmotic pressure

Fig. 7 shows the relationship between the feed concentration (C_F), the concentration of lactate on the membrane surface (C_M) and the osmotic pressure ($\Delta\pi$) for the HLa solution, NH_4La solution and fermentation broths at a feed flow rate of 6.4 L/min ($Re = 540$). The dotted line is the osmotic pressure of the HLa model solution (pH 1.8), calculated at $T = 25^\circ C$ with a van't Hoff coefficient ($i = 1.0$). The dashed line is the osmotic pressure of NH_4La (pH 5.4) calculated at $T = 25^\circ C$ and $i = 2$. The results show that, for both the HLa and NH_4La solutions, the osmotic pressure for a given C_F is higher than that calculated by the van't Hoff eq. ($i = 1, i = 2$). Due to concentration polarization, C_F tends to C_M (indicated by dotted-dashed line).

The relationship between osmotic pressure obtained

Table 1 The osmotic pressure of various solutions

Run	Symbol (in Fig. 7)	Solution	Feed solution conditions				Osmotic pressure		
			C_{So} [g/L]	D_r [h ⁻¹]	C_{La} [g/L]	C_{RS} [g/L]	①	②	① - ② [MPa]
							$\Delta P_{Jv=0}$ [MPa]	$\Delta\pi$ (from Eq.(11)) [MPa]	
B1	▲	Fermentation broth by batch process	20	-	18.3	0.01	1.64	0.94	0.70
B2	●		25	-	19.9	0.03	1.70	1.03	0.67
B3	■	Fermentation broth by continuous process	25	0.2	14.8	8.7	2.45	0.76	1.69
B4	◆		40	0.1	29.3	8.3	2.94	1.54	1.40
B5	△	Fresh medium	-	-	-	-	0.62	-	-
B6	○	Fresh medium with sugar	-	-	-	8.5	1.32	-	-

from the experiment and feed concentration of lactate for the NH₄La solution is given in the following equation by second order of least-square method.

$$\Delta\pi = 1.11 C_{La}^2 + 5.33 C_{La} \quad (11)$$

where C_{La} is the lactate concentration.

The osmotic pressures of various solutions are listed in Table 1. For the fermentation broth produced by the batch process, the osmotic pressure for runs B1 and B2 was 1.64 MPa and 1.70 MPa, respectively. The calculated osmotic pressures of the model NH₄La solutions for the same lactate concentration were 0.94 MPa and 1.03 MPa for runs B1 and run B2, respectively, using Eq. (11). The difference in the osmotic pressure between the fermentation broth and the NH₄La solution was about 0.70 MPa for run B1 and 0.67 MPa for run B2. This is probably due to the presence of medium in the fermentation broth. An RO experiment with fresh medium was then conducted in the same conditions, and the osmotic pressure was measured (run B5) by the same method. It was found that the osmotic pressure of fresh medium was 0.62 MPa. This value was near to the difference in osmotic pressure the fermentation broth and the model NH₄La solution. Note that the experimental line in Fig. 7 (runs B1, B2 and B5) is parallel to the curve for the NH₄La solution, calculated by the van't Hoff eq. ($i = 2$). It can thus be understood that the presence of medium in the fermentation broth contributes to the increase of the osmotic pressure.

The osmotic pressure of the fermentation broths produced by the continuous process (runs B3 and B4) are also listed in Table 1. The osmotic pressures of the fermentation broths in runs B3 and B4 were 2.45 MPa

and 2.94 MPa, respectively. Meanwhile, the osmotic pressures calculated for the model NH₄La solutions for the same lactate concentrations were 0.76 MPa and 1.54 MPa, respectively, from Eq. (11). The differences in osmotic pressure between the fermentation broth and the model NH₄La solution were 1.69 MPa and 1.40 MPa for runs B3 and B4, respectively. These could be due to the presence of medium and residual sugar in these broths. An RO experiment was then conducted using fresh medium containing 8.5 g/L of sugar (run B6). The osmotic pressure of the solution was 1.32 MPa. This value slightly less than the difference in osmotic pressure between the fermentation broth and model NH₄La solution. The presence of residual sugar could also increase the viscosity of the fermentation solution, resulting in a reduction of the Reynolds number and an increase in the concentration of solute on membrane surface due to concentration polarization. This makes sense because the estimated osmotic pressure of the NH₄La solution at a lower Re is higher than that at a higher Re number. Thus, the difference between them became too small. The experimental line in Fig. 7 (runs B3, B4 and B6) is parallel to the curve for the NH₄La solution calculated by the van't Hoff eq. ($i=2$). Hence, it can be understood that residual sugar in the fermentation broth contributes to an increase in osmotic pressure.

4.5 Concentration process for fermentation broth by batch operation

Fig. 8 shows the relationship between permeate flux and the lactate concentration at a transmembrane pressure of 5.5 MPa and initial feed flow rate of 6.4 L/min ($u = 0.70$ m/s, $Re = 540$). It can be seen that for all solutions, the permeate flux decreased as the concen-

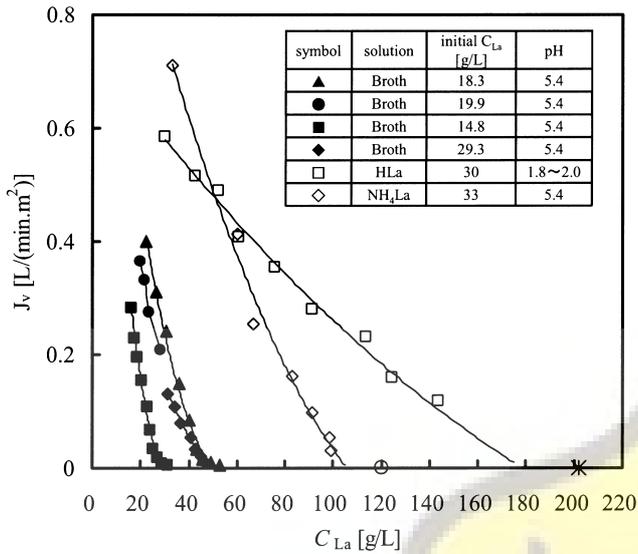


Fig. 8 Relationship between permeate flux with lactate concentration at transmembrane pressure of 5.5 MPa and initial feed flow rate of 6.4 L/min.

tration of lactate increased during batch operation. The final concentration reached was predicted to be 175 g/L and 105 g/L for HLa and NH₄La model solutions, respectively. The actual concentration factor was found to be about 5.8 times for HLa solution and 3.2 times for NH₄La solution. When the osmotic pressure equaled the transmembrane pressure (5.5 MPa), the concentration of the HLa and NH₄La solutions was calculated to be 201 g/L (symbol : *) and 120 g/L (symbol :), respectively. The experimental results for the degree of concentration of the HLa and NH₄La solutions were lower than the predicted values due to concentration polarization.

For fermentation broth produced by a batch process (symbols: triangles and circles) without residual sugar and an the initial lactate concentration of 18.3 and 19.9 g/L, the final concentration of lactate was about 58 g/L, yielding a concentration factor of about three. For fermentation broth produced by the continuous process (symbols: squares and rhombuses), the lactate is seen to have increased in concentration from 14.8 g/L to 31 g/L and from 29.3 g/L to 46.3 g/L, yielding concentration factors of 2.0 and 1.6, respectively. The concentration factors of lactate in fermentation broth produced by batch and continuous processes were lower than that of the model NH₄La solution due to osmotic pressure from the medium and residual sugar, in addition to the concentration polarization effect. The concentration factor of fermentation broth produced by

the continuous process was lower than that produced by batch process due to the presence of residual sugar.

Presti and Moresi¹⁴⁾ reported the recovery of lactic acid from aqueous solution by thin-film composite, spiral-wound RO. They found that for various transmembrane pressures, the concentration factor of each component was only about two, due to the increasing osmotic pressure with increasing concentration of solute.

Because the concentration factor of lactic acid by reverse osmosis is not sufficiently high, we propose two stages process which combined reverse osmosis in the first stage and distillation in the second stage. This system is expected to reduce the energy required for separation and concentration of lactic acid comparing to that of conventional distillation.

5. Conclusions

Separation and concentration of lactic acid from cassava fermentation broth by a disk-type plate-and-frame reverse osmosis module was investigated. Model solutions of lactic acid and ammonium lactate were used as standard solutions. The effects of operating conditions (feed velocity, transmembrane pressure, and feed concentration) on permeate flux, rejection and osmotic pressure were studied. It was found that permeate flux increased with increasing feed velocity, from 0.34 m/s (Re = 250) to 1.5 m/s (Re = 1100). In contrast, permeate flux was not affected by feed velocity above 1.5 m/s because turbulent flow eliminated the effect of concentration polarization on the membrane surface. Moreover, permeate flux and rejection increased with increasing transmembrane pressure, whereas an increase in the feed concentration resulted in decreases in both permeate flux and rejection as well as an increase in osmotic pressure.

Model solutions of lactic acid and ammonium lactate can be concentrated 5.8 and 3.2 times, respectively, at an initial concentration of 30 g/L, a transmembrane pressure of 5.5 MPa and under conditions of laminar flow (initial feed velocity of 0.70 m/s, Re = 540). For the fermentation broth, the lactic acid concentration factor was about 2.0 times and 1.6 times without residual sugar (produced from batch fermentation) and with residual sugar (produced from continuous fermentation), respectively, at a transmembrane pressure of 5.5 MPa. It can thus be understood that the presence of

medium and residual sugar leads to an increase in osmotic pressure and a decrease in the concentration factor.

Nomenclature

\bar{C}_s	= average concentration of solute	[g/L]
C_F	= feed concentration	[mol/L]
C_M	= concentration on the membrane surface	[mol/L]
C_P	= permeate concentration, k is mass transfer coefficient	[mol/L]
C	= difference in the concentration of solute on membrane surface and permeate side	[mol/L]
C_{S0}	= initial concentration of substrate	[g/L]
C_{La}	= lactate concentration	[mol/L] or [g/L]
C_{RS}	= residual sugar concentration	[g/L]
D	= diffusion coefficient	[m ² /s]
D_r	= dilution rate	[h ⁻¹]
F_i	= feed flow rate	[L/min]
i	= van't Hoff coefficient	[-]
J_s	= permeate flux of solute	[kg/(min·m ²)]
J_v	= permeate flux	[L/(min·m ²)]
L_p	= permeability coefficient	[L/(min·m ² ·MPa)]
n	= total number of ions provided by one formula unit.	[-]
P	= transmembrane pressure	[MPa]
Re	= Reynolds number	[-]
R	= universal gas constant	[8.314 Pa·m ³ ·mol ⁻¹ ·K ⁻¹]
R_{obs}	= observed rejection	[-]
R_{int}	= intrinsic rejection	[-]
T	= absolute temperature	[K]
u	= feed velocity	[m/s]
	= dissociation degree	[-]
b	= thickness of the boundary layer over which the concentration gradient exists	[m]
m	= thickness of the membrane	[m]
	= osmotic pressure difference across membrane	[MPa]
	= reflectivity coefficient	[-]
	= permeability of solute	[L/(min·m ² ·MPa)]

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