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Chemical Interactions Between Aqueous and Organic Phases in a Reactive Extraction Process

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ABSTRACT

Partitioning of lactic acid between aqueous phase and kerosene containing tri-*n*-octyl phosphine oxide (TOPO) as a reactive agent was measured and analyzed in terms of an association model between lactic acid and TOPO. Equilibrium association was calculated to involve 1.1 mol of lactic acid/mol of TOPO. ^{31}P-NMR and FT-IR analyses found no evidence of covalent bond formation between lactic acid and TOPO in solutions in kerosene, and pointed to hydrogen bond formation between the two chemicals. In a hydrophobic, microporous, hollow-fiber-membrane module, the simultaneous presence of lactic acid, TOPO, and the back-extractant NaOH resulted in drastic membrane fouling as evidenced by the loss of kerosene flux through the membrane. The membrane could be restored back to the original kerosene flux after extensive washing.

Index Entries: Partition coefficient; NMR; FT-IR; lactic acid; Tri-*n*-octyl phosphine oxide.

INTRODUCTION

A number of commercially important products of biological origin express toxicity towards the biological agents that produce them *(1,2)*. This results in dilute solutions of the products, reduced observed yields, low production rates, and increased costs of product recovery. Hence, on-line methods of product recovery are being aggressively explored. Of these, solvent extraction is particularly attractive owing to the possibility of engineering high selectivity for desired compounds and the potential for not only minimizing the product toxicity but also reducing the need for extensive downstream processing *(4,5)*. Unfortunately a number of solvents with high product specificity and good partitioning characteristics, are toxic towards the microorganisms that produce the biological products *(5)*. Solvent toxicity has been

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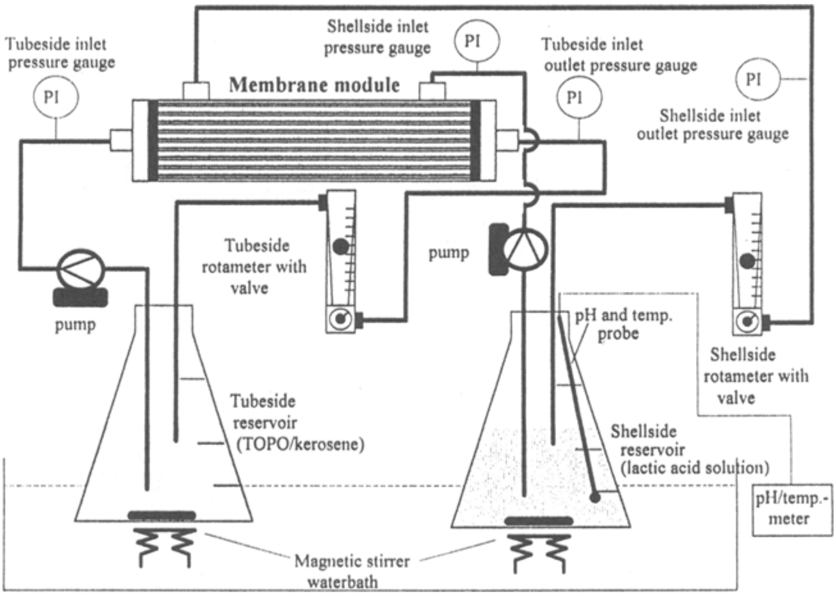

Fig. 1. A schematic of a membrane-associated reactive extraction system for recovery of lactic acid from fermentation broths.

demonstrated to stem from the solubilized solvents in the aqueous phase and from the exposure of the microorganisms to the solvent–aqueous phase interface *(5,6)*. In this respect, solvent extractions in which microporous membranes are used to separate the solvent and aqueous phases are promising, since they eliminate the problems of interfacial toxicity while reducing the costs associated with creation and maintenance of dispersions *(7–9)*. A schematic of such a process for lactic acid fermentation has been presented in Fig. 1. This process involves reactive extraction of lactic acid from the fermentation broth into a mixture of kerosene and tri-*n*-octyl phosphine oxide (TOPO). Additionally, the presence of a membrane barrier between the aqueous and solvent phases has been further exploited by using a dispersion of alkali droplets in solvent. These alkali droplets back-extract lactic acid from the solvent phase and enhance extraction of the organic acid from the fermentation broth. Separation of the neutralized alkali droplets from the solvent phase has been shown to produce a concentrated stream of purified sodium lactate *(9)*.

Incorporation of such reactive systems in a scheme for on-line product recovery poses a number of questions regarding their ramifications on the fermentation and the extraction process. The objective of the present research was to address these questions. The specific objectives were to study: (1) the interactions between the reactive agent TOPO and lactic acid, and (2) the effect of TOPO and other components present in the aqueous and solvent phases on membrane fouling.

MATERIALS AND METHODS

TOPO was obtained as 98% pure chemical from Aldrich Chemical Co. (Milwaukee, WI). It was dissolved in kerosene obtained from Phillips Petroleum Co. (Bartlesville, OK). Kerosene was washed twice with equal amounts of deionized water to remove water-soluble chemicals and passed through a 0.2-µm filter before use. The solubility of TOPO in kerosene was found to be 19.7% (w/w) at 20 ± 1°C. Lactic acid solutions were prepared by diluting 88% lactic acid stock solutions (Pfalz and Bauer) to either 8 or 16% concentration. Measurements of equilibrium partitioning coefficients of lactic acid in kerosene with or without TOPO were conducted at 37°C in Erlenmeyer flasks. After contacting the two phases for 24 h at an agitation rate of 200 rpm in a rotary incubator, the two phases were separated. Lactic acid concentration in the aqueous phase was determined directly by HPLC using a procedure described previously *(5)*. The concentration of lactic acid in the organic phase was similarly determined after back-extraction of lactic acid in sodium hydroxide solution.

The experimental setup shown in Fig. 1 was procured from Hoechst-Celanese Corporation (Charlotte, NC). It consisted of Liqui-Cel Laboratory Liquid–Liquid Extraction system 5PCS-100 and the Liqui-Cel Laboratory Membrane Contactor 5PCM-106. It contained 2100 Celgard X-10 microporous polypropylene hollow fibers (internal diameter 210 µm, external diameter 300 µm, length 16 cm, effective pore diameter 0.05 µm, porosity 30%, and effective surface area 0.23 m^2). Changes in kerosene flux through the membrane at a transmembrane pressure of 29 psi were used as measures of membrane fouling. Membrane permeability was independent of the transmembrane pressure. Membrane extractions were conducted at 37 ± 0.5°C by countercurrent flow of organic phase through the tube side (250 mL/min) and aqueous phase on the shell side at the same flow rate. Details of these measurements have been presented by Scheler *(10)*.

RESULTS AND DISCUSSION

Interactions Between Lactic Acid and TOPO in Kerosene

Equilibrium partitioning of lactic acid between water and TOPO in kerosene was measured at different concentrations of lactic acid and TOPO. The distribution coefficients (m) and partition coefficients (m^*) were calculated from the concentrations of lactic acid in the two phases according to the following definitions:

$$\text{Distribution coefficient } (m) = (C_{\mathrm{LAorg}}/C_{\mathrm{LAaq}}) \tag{1}$$

and

$$\text{Partition coefficient } (m^*) = (C_{\mathrm{HAorg}}/C_{\mathrm{HAaq}}) = m^* \,(1 + 10^{\,\mathrm{pH-pK}}) \tag{2}$$

where LA represents the concentration of total lactic acid and HA the concentration of undissociated lactic acid. pH is the negative logarithm of hydrogen ion concentration in aqueous medium at equilibrium, and pK is the negative logarithm of equilibrium dissociation constant of lactic acid.

The partition coefficient data have been presented in Fig. 2. These decrease linearly with increasing total lactic acid concentration and increase with increasing TOPO concentration. Similar results were also obtained by Golob et al. *(11)* and by Kuo and Gregor *(12)*. Experiments were also conducted with technical-grade TOPO and at room temperature (25°C). However, no significant differences were found between the partition coefficients with technical and analytical grades of TOPO. Within the temperature range, the effect of temperature was also minimal.

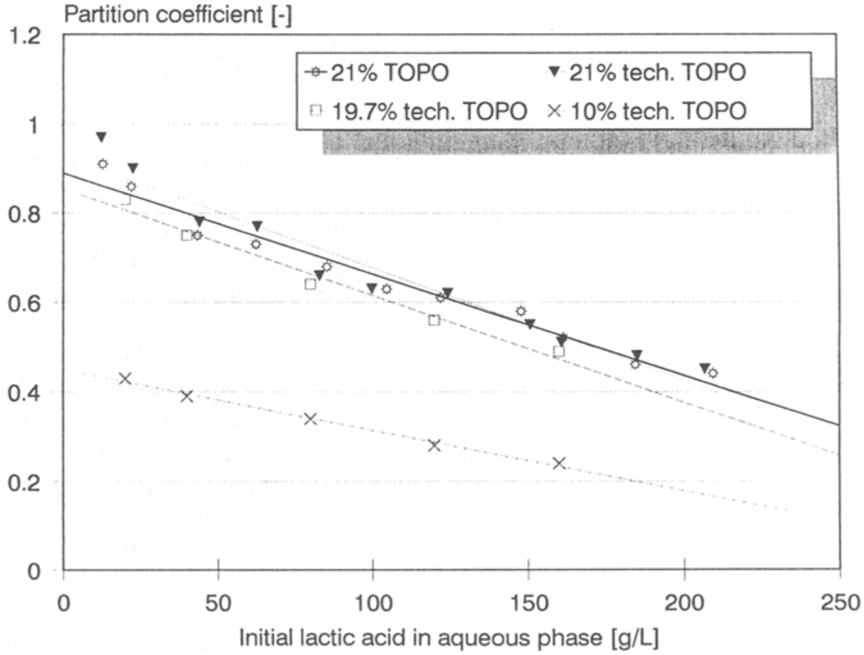

Fig. 2. Measured partition coefficients for lactic acid between aqueous phase and kerosene/TOPO.

A phase equilibrium model of the type proposed by Fahim et al. *(13)* was used to analyze the partition coefficient data. According to this model, if the interactions between lactic acid in aqueous phase and TOPO in the solvent phase are written as:

$$n\mathrm{HA} + \mathrm{S_o} \rightleftharpoons [\mathrm{HA}]^n\mathrm{S_o} \qquad (3)$$

the partition coefficient can be derived to be:

$$\text{Partition coefficient} = m^* = n\mathrm{K_1}\,(\mathrm{HA_{aq}})^{n-1}[(\mathrm{S_{oT}}) - (\mathrm{HA_o}/n)]$$

Here, n is the number of molecules of undissociated acid HA that are associated with 1 molecule of TOPO in the organic phase, and $\mathrm{K_1}$ is the association constant of the organic acid with the reactive agent. $(\mathrm{S_{oT}})$ is the total amount of lactic acid per unit volume of aqueous phase. Thus, a Log-Log plot of m^* and $[\mathrm{HA_{aq}}]^{n-1}\,[(\mathrm{So_T}) - (\mathrm{HA_{aq}})/n]$ should lead to a straight line of slope 1.0. Since the number (n) of acid molecules associating with 1 molecule of TOPO is not known, different values of n were chosen with the objective of achieving a slope of 1.0 for the line of best fit between the experimental data presented in Fig. 2 and the predictions of Eq. *(3)*. Based on such calculations, a value of $n = 1.1$ was obtained. The plot of partition coefficient against the function mentioned above has been presented in Fig. 3. Such values for n for association of organic acids with reactive agents are in agreement with the observations of Fahim et al. *(13)*, who reported a value of 1.4 for acetic acid—TOPO interactions. Similar numbers were found for propionic acid—TOPO also.

Noninteger numbers associated with reactive agents are difficult to comprehend. Further investigations of the interactions between lactic acid and TOPO in kerosene were conducted. These methods involved investigation of TOPO–lactic acid complexes with the help of FT-IR and ^{31}P-NMR techniques.

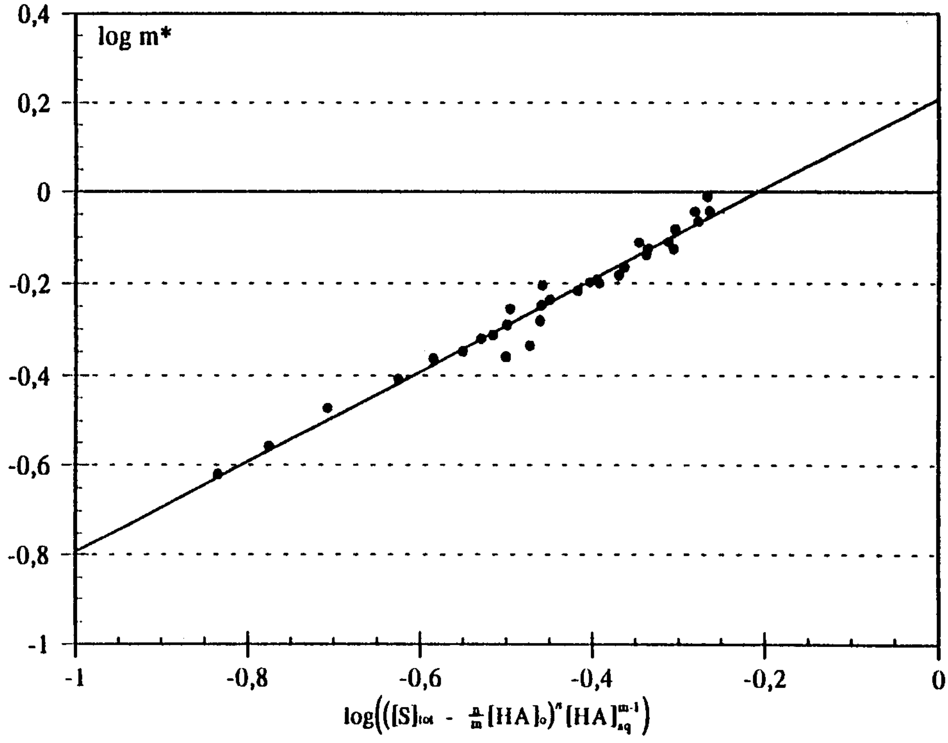

Fig. 3. Representation of partition coefficient data according to equation *(3)*.

^{31}P-NMR and FT-IR Studies of TOPO–Lactic Acid Complexes

^{31}P-NMR studies were conducted at different concentrations of lactic acid to study the nature of the lactic acid–TOPO complex in kerosene. In all the cases, only one peak was observed suggesting a rapid, reversible, and equilibrium association between the two constituents of the complex. The absolute chemical shift at which the peak occurred was found to change with the concentration of lactic acid in the kerosene–TOPO solution (Fig. 4). Yet the changes were small compared to the expected shift if any covalent bonds were formed between TOPO and lactic acid. Owing to the small changes in the absolute chemical shift, it is concluded that ≡P=O group in TOPO remains essentially unaffected by the presence of lactic acid molecules, and the nature of this interaction is mostly through hydrogen bonding. Kuo and Gregor *(12)* have also reported formation of hydrogen bond between the TOPO and acids. Similar conclusions were also made from the results of FT-IR analysis. FT-IR spectra of TOPO in kerosene, aqueous solution of lactic acid, and of lactic acid partitioned in kerosene/TOPO are presented in Fig. 5. Neither did the presence of lactic acid influence the position of phosphate group in TOPO, nor was there any effect of TOPO on the wavelength for the carbonyl group.

Effect of the Reactive Solvent System on Kerosene Flux Through the Membrane

A number of experiments were conducted where different organic (tube side) and aqueous (shell side) phases were pumped through the membrane system at a flow rate of 250 mL/min for 5 h. After each experiment, the kerosene flux through

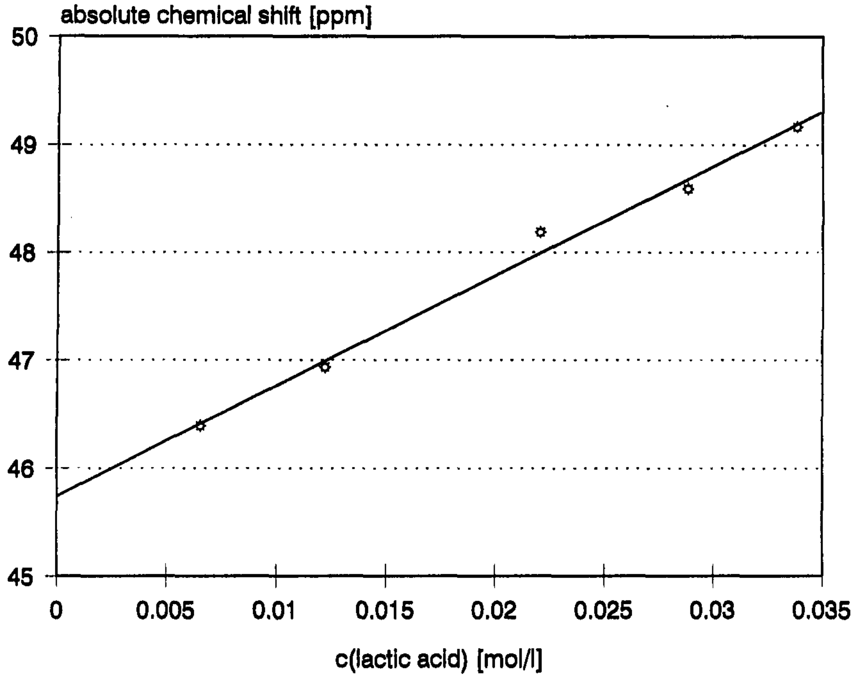

Fig. 4. Absolute chemical shift as a function of lactic acid concentration in ^{31}P-NMR.

the membrane pores was measured at 29 psi and compared with the flux before exposure to the extractants. The results are presented in Table 1 where positive fouling was indicated for cases where the kerosene flux decreased by at least 80% as a result of the extraction process. Clearly, a severe reduction in kerosene flux was observed when TOPO, NaOH, and lactic acid were simultaneously present in the system. A ^{31}P-NMR spectrum of TOPO–lactic acid–NaOH in kerosene did not reveal any additional complex formation at the phosphate bond. It is possible that the presence of these three chemicals together causes a physical change, such as precipitation or formation of stable emulsions, which has been reported earlier *(11)*. Wang et al. *(14)* have reported that crystals of TOPO were observed on the membranes that were exposed to air after the experiments. Therefore, the membrane was not exposed to air after coming in contact with TOPO.

Figure 6 shows electron micrographs of a fresh membrane and of one in which the kerosene flux had dropped. These observations support the formation of a precipitate when the three chemicals (TOPO, NaOH, and lactic acid) are present together in the membrane system. This fact is also supported by the measurements conducted during an attempt to clean the fouled membrane with the objective of restorinf the kerosene flux. These procedures and the results have been presented in Table 2. The extensive cleaning restored the membrane to its original condition. Whether the formation of the precipitate results in a corresponding loss of extractive flux of lactic acid is an open question. Our earlier measurements *(14)* and some of the recently conducted measurements suggest that the extractive flux of lactic acid does not drop as rapidly.

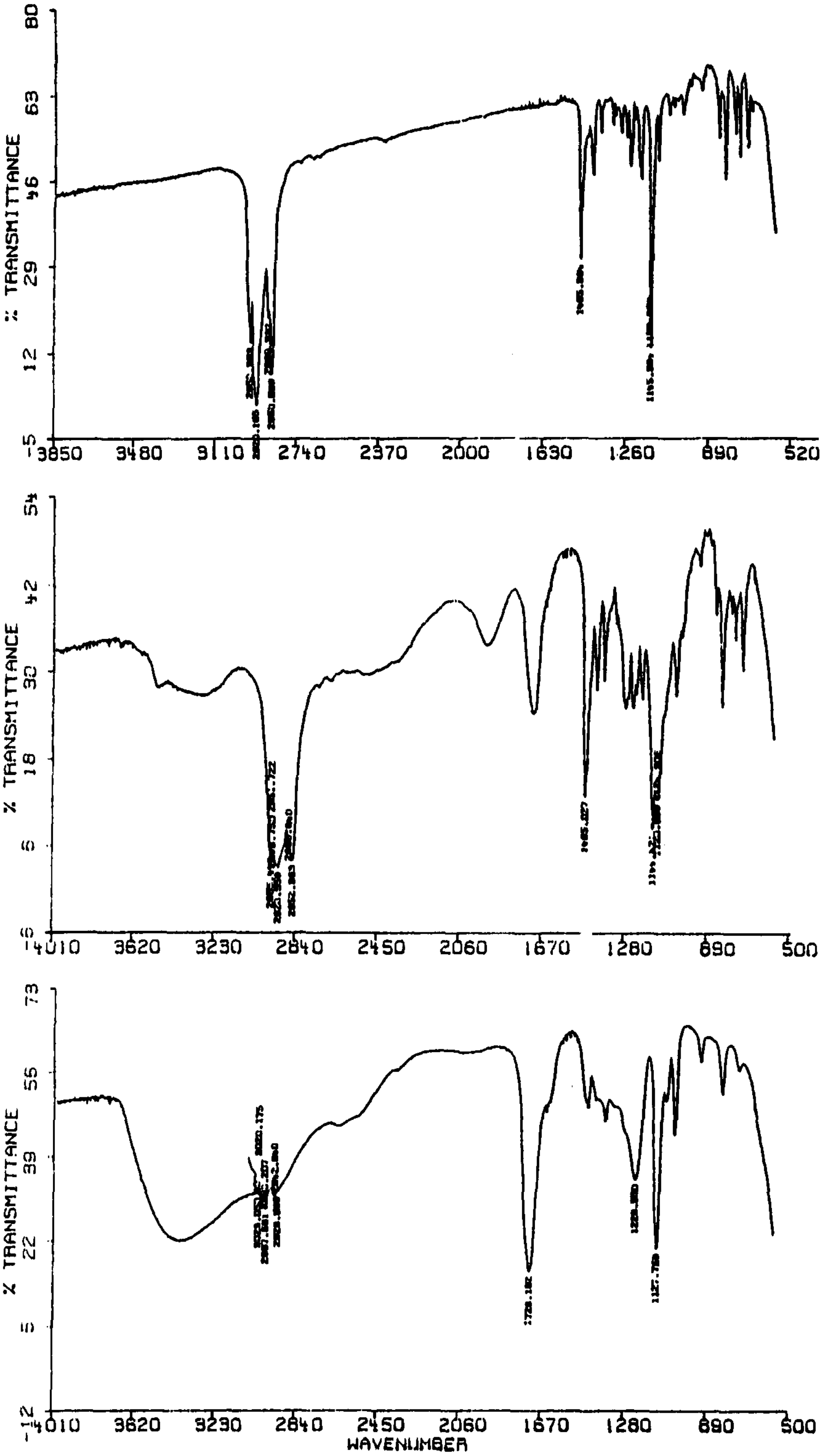

Fig. 5. FT-IR spectra of solutions of TOPO in kerosene, lactic acid in water, and TOPO-lactic acid in kerosene.

Table 1
Operational Conditions That Result in Fouling of Membranes
During Extractive Recovery of Lactic Acid from Aqueous Phase

Tube side	Shell side	Fouling % flux change
10% TOPO in kerosene with 20 vol% 2*N* NaOH dispersed	8% Lactic acid, pH 4	+ (−80 ± 1)
Supported liquid membrane formed with 10% TOPO in kerosene in membrane pores and 2*N* NaOH on shell side	8% Lactic acid, pH 4	+ (−85 ± 1)
10% TOPO in kerosene	8% Lactic acid, pH 4	– (+8)
Kerosene	8% Lactic acid, pH 4	– (–1)
20 vol% 2*N* NaOH in kerosene	8% Lactic acid, pH 4	(+1)
10% TOPO in kerosene	2*N* NaOH	– (+1)
10% TOPO in kerosene with 20 vol% 2*N* NaOH dispersed	Distilled water	– (+1)

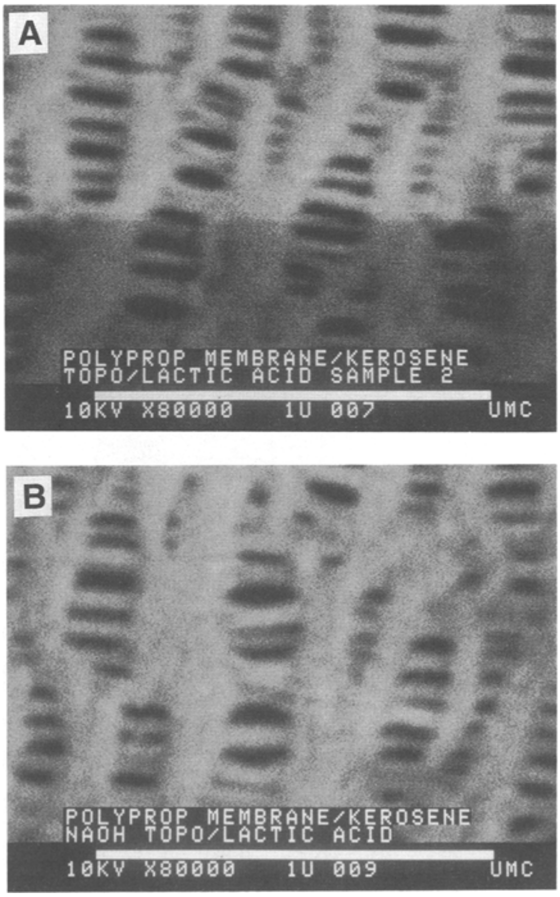

Fig. 6. Electron micrographs of clean and fouled membranes.

Table 2
Kerosene Flux Through Membrane Before and After an Extraction Experiment and During Successive Cleaning Steps

Process	Kerosene flux in L/(m²h) at 29 psi TMP	
	Before	After
Extraction with kerosene/TOPO/NaOH	42	7.8
20 h Storage in kerosene	7.8	7.8
1 h Washing with kerosene at 55°C	7.8	24
3 h Storage in kerosene at room temperature	24	13.2
1 h Washing with 50% isopropanol at 54°C	13.2	13.2
Storage in kerosene for 20 h at room temperature	13.2	41.4

CONCLUSIONS

Partition coefficient of lactic acid between aqueous and organic phase (kerosene + TOPO) increases linearly with increase in the concentration of TOPO in kerosene and decreases with increase in the concentration of lactic acid. On the average, 1.1 mol of lactic acid can associate with each molecule of TOPO in the organic phase. There is no covalent bond formation between TOPO and lactic acid in the organic phase. NMR and FT-IR data suggest that a hydrogen-bond formation is more likely. The presence of TOPO, lactic acid, and NaOH together in the membrane system causes a rapid drop in the transmembrane flux of kerosene. The kerosene flux could be restored to its original value only after extensive cleaning.

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