Effect of Number of Bipolar Membranes and Temperature on the Performance of Bipolar Membrane Electroacidification

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The purpose of this study was to evaluate the effects of stacking bipolar membranes (1−4 BPMs) on the energy and electroacidification parameters, as well as the temperature (10, 20, and 35 °C) on the efficiency of bipolar membrane electroacidification (BMEA) of soybean protein for the production of isolate. BMEA is based on the production of protons by dissociation of water molecules at the interface of bipolar membranes. Increasing the surface of bipolar membranes accelerates the electrochemical precipitation in a quasilinear fashion, while also increasing the electrical efficiency. The stacking has no effect on the final protein precipitation rate. The main effect of increasing the temperature from 10 to 35 °C appears to be a decrease in the duration of the procedure (30.42 vs 26.79 min) as well as increasing the energy efficiency. Increasing temperature slows the precipitation of proteins by decreasing hydrophobic interactions.

Keywords: *Temperature; bipolar membrane; stacking; electroacidification; soya protein*

INTRODUCTION

The nutritional and technological importance of soya protein (63% of plant protein consumed worldwide) (Soyatech Inc., 1993) in agricultural and food products has, for several years, been a driving force behind the study of this class of food products and the development of industrial processes intended to separate them and improve their properties and qualities.

Bipolar membrane electroacidification (BMEA) of proteins is a recent technology derived from electrodialysis. This procedure is intended to precipitate proteins in order to separate them from other constituents and to concentrate these proteins while preserving their functional properties (Bazinet *et al.*, 1996, 1997). A centrifugation of the protein solution can be used for a simple separation of proteins precipitated in solution. Electrodialysis uses an electric field as a driving force and charged membranes as a separating agent (Lopez Leiva, 1988a,b). The strategy adopted in electroacidification is based on the production of protons by the dissociation of water at the interface of a bipolar membrane (BPM), driven by a voltage difference. BPMs have a composite structure as they are composed of three parts: an anion exchange layer, a cation exchange layer, and a hydrophilic interphase at their junction. When an electric current is applied, electron transport is assured by the H^+ and OH^- ions from the dissociation of water at the interface (Mani, 1991). Currently, the main uses for BPMs in electrodialysis are in the area of production of acids and bases (Mani, 1991), the production of lactic acid (Siebold *et al.*, 1995) and propionic acid (Boyaval *et al.*, 1993) concentrates, and the inhibition of enzymatic browning in cloudy apple juice (Tronc *et al.*, 1997).

BMEA has specific advantages over the conventional isoelectric precipitation of soya proteins used industrially for the production of soybean protein isolates. This technology does not use any chemical acids or bases during the process to decrease or increase the pH of the protein solution, and the chemical effluents generated during the process could be reused at different stages in the process. In addition, the chemical composition of the electroacidified sample was demonstrated to be superior or equal to that of commercial standards, with functional properties comparable to these standards (Bazinet *et al.*, 1996).

In a previous work, we studied the effect of the concentrations of KCl and soya protein concentrate (SPC) on the performance of bipolar membrane electroacidification, to optimize the solution concentration factors (Bazinet *et al.*, 1997). The purpose of this study is to evaluate the effect of stacking bipolar membranes (one to four BPMs) on the energy and electroacidification parameters, and the temperature (10, 20, and 35 °C) on the efficiency of bipolar membrane electroacidification. The temperature studies are evaluated in terms of energy, power consumption, and percentage of precipitated proteins. The analysis of the ash content of electroacidified proteins led to a deeper understanding of the overall ionic changes in solution during the procedure, as carried out at different temperatures.

MATERIALS AND METHODS

Material. The crude protein concentrate (60% protein) used in this study was obtained as follows: a given quantity of deoiled soya flakes (6 kg) (Central Soya, Woodstock, ON, Canada) was added to 54 L of distilled water. The mixture was heated to 50 °C, and the pH was adjusted to 8. The mixture was stirred for 30 min, and the insoluble material was removed by basket centrifugation (Type SBW11, Western States, Hamilton, OH) and a press filter (1 μm) (Model 6SS4-812-TIHO, StarSystems, Timmonsville, SC). The liquid was then rapidly frozen and lyophilized. The final product was stored at 4 °C. The SPC contained 57.5% protein, 11.2% carbohydrate, 1.8% fat, and 8.7% ash, expressed as percentage of dry matter.

Methods. *(a) Electroacidification Cell.* The module used was an MP type cell (100 cm^2 of effective surface) purchased

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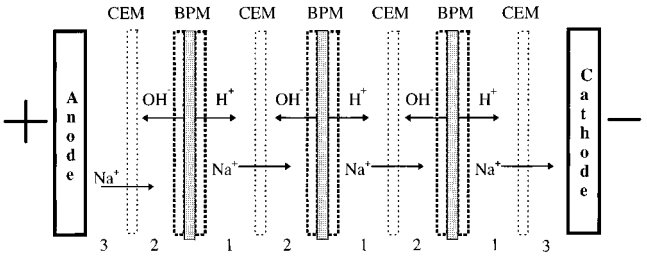

Figure 1. Bipolar membrane electroacidification cell. CEM, cation exchange membrane; BPM, bipolar membrane.

from Electrosynthesis Co. Inc. (model MP Electrocell AB, Lancaster, PA). The cell was assembled as shown in Figure 1. It consists of three circuits containing the protein solution (circuit 1), a 2 g L^{-1} aqueous KCl solution (circuit 2), and a 20 g L^{-1} Na_2SO_4 solution (circuit 3). These circuits were separated by CR-64-LMP-401 cationic membranes (Ionics Inc., Watertown, MA) and Neosepta BP-1 bipolar membranes from Tokuyama Soda Ltd. purchased from Electrosynthesis Co. Inc. (Lancaster, PA). Each circuit was connected to a separate external 10 L reservoir, allowing for continuous recirculation.

The anode/cathode voltage difference was supplied by a variable 0−100 V power source (Powerstat Model 236BU-2, The Superior Electric Co., Bristol, CO). The three electrolytes were circulated using three centrifuge pumps (Model XVB56C34F2012b-W, Marathon Electric, Wausau, WI), and the flow rate was controlled at 4.5 L min^{-1} using Filter-Chem flowmeters (Model FC-FI-C-3/8, Alhambra, CA). The electrolytes were maintained at constant temperature by circulating water inside a stainless steel coil immersed in each of the three reservoirs. The anode, a dimensionally stable electrode (DSA), and the cathode, a 316 stainless-steel electrode, were supplied with the MP cell (Figure 2).

(b) Effect of the Number of Bipolar Membranes. Cells arrangements consisting of 1−4 membranes were used to investigate the impact of multiple membranes on the energy efficiency of the procedure. The electroacidification was performed in batch process using a current of 2.5 A, on solutions containing 30 g L^{-1} of SPC and 0.12 M KCl, at a constant temperature of 20 °C with electrolyte volumes of 6 L. The initial pH ranged from 7.3 to 7.6. Three replicates of each of the arrangements were performed.

(c) Effect of Temperature. The protein solution which was electroacidified contained 30 g L^{-1} of SPC and 0.06 M KCl. A previous study on the effect of KCl and SPC concentration demonstrated that at 30 g L^{-1} SPC, a minimal salt concentration was necessary for effective electroacidification (Bazinet *et al.*, 1997). To study the effect of temperature, the KCl concentration was decreased to 0.06 M in order to decrease the effect of salting in observed at pH 4.5. The initial pH varied between 8.3 and 8.0 depending on the temperature. Three replicates were performed at three different temperatures (10, 20 and 35 °C). During each run, the protein solution was sampled at the initial pH and at pH values of 7, 6, 5, and

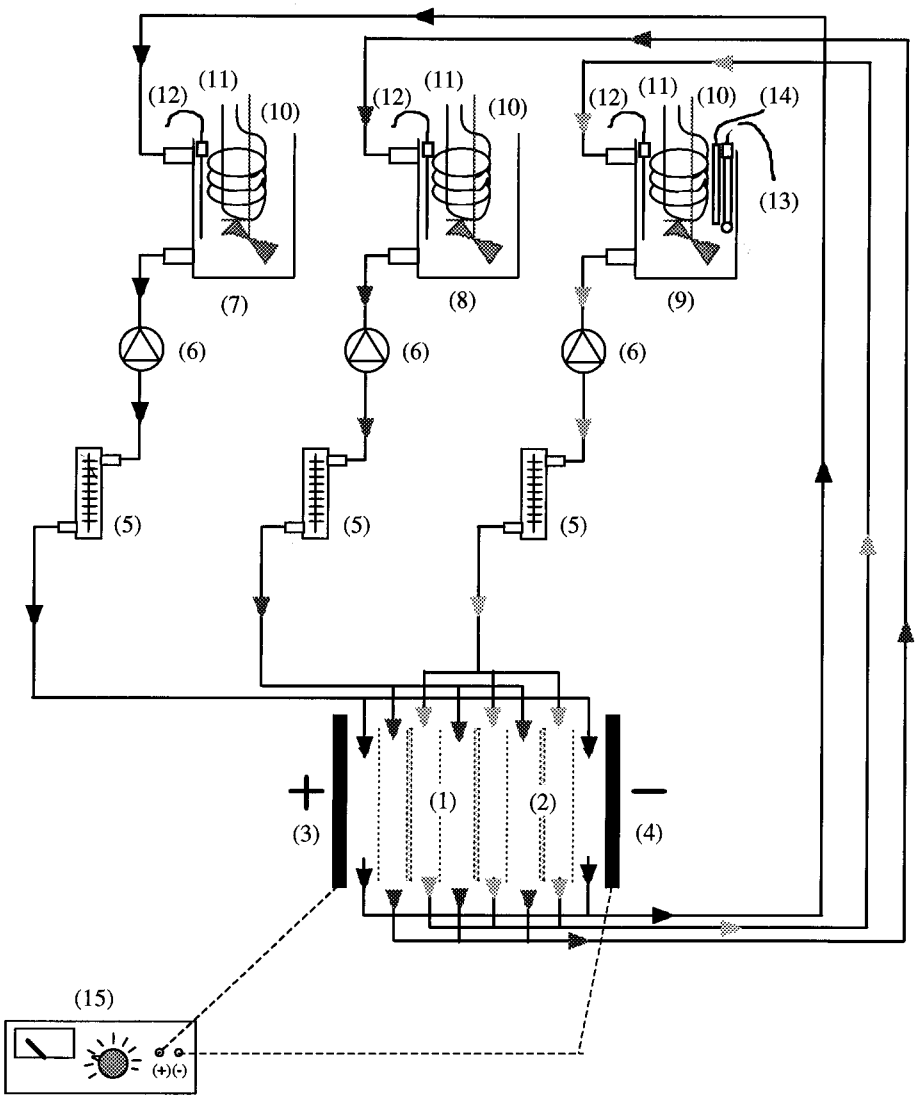

Figure 2. Schematic diagram of a three bipolar membrane arrangement batch recirculation electro-acidification: (1) cation exchange membrane; (2) bipolar membrane; (3) anode; (4) cathode; (5) flowmeter; (6) centrifugal pump; (7) Na_2SO_4 compartment; (8) KCl compartment; (9) protein compartment; (10) stirring paddle; (11) stainless-steel coil; (12) thermocouple; (13) pH meter; (14) conductivity meter; (15) power supply.

4.5. The samples were stored at −40 °C until they were lyophilized. Various analyses, including the concentration of soluble proteins and the ash content, were performed in order to better understand the electroacidification phenomenon.

The time required to reach pH 4.5, as well as the anode/cathode voltage difference and the conductivity of the solution during the course of the experiment were also recorded. The power and energy consumption for each treatment were determined to measure the electrical efficiency of the procedure (Sappino *et al.*, 1996; Pérez *et al.*, 1994; Lopez Leiva, 1988a). The voltage as a function of the time multiplied by the current was integrated according to the following equation:

$$E = \int_{t_0(\text{pH 7.3 or 8.0})}^{t_x(\text{pH 4.5})} I/60 \times U \, dt \qquad (1)$$

where U = voltage (V), I = current (A), t = time (min), and E = energy (J).

(d) Analysis Methods: Anode/Cathode Voltage Difference. The voltage was read directly from the indicators on the power supply (Powerstat Model 236BU-2, Superior Electric Co., Bristol, CO).

Conductivity. A YSI conductivity meter (Model 35, Yellow Springs, OH) was used with a YSI immersion probe (Model 3417, cell constant $K = 1$ cm^{-1}, Yellow Springs, OH) to measure the conductivity of the protein solutions.

Soluble Protein Concentration. The protein solubility was measured using the Bradford method (1976) at 595 nm on a Beckman spectrophotometer (Model DU 640, Fullerton, CA). The method was calibrated each time with a BSA standard from 0 to 1.4 g/L.

Ash Content. Crucibles were washed beforehand in nitric acid (HNO_3, 3 N), rinsed with deionized water and dried in a 100 °C oven for 1 h. They were removed from the oven and placed in a desiccator. Approximately 1 g of lyophilized sample was added to the cooled crucibles, and the weight was recorded. The samples were then ashed at 600 °C for at least 16 h. The samples were allowed to cool to room temperature in a desiccator and weighed again.

(e) Statistical Analyses. The data on the duration of the electroacidification, and the measurements of voltage and conductivity as a function of time, were subjected to an analysis of variance using SAS software (SAS, 1989). Regression equations were calculated for the anode/cathode voltage difference and conductivity, as a function of pH, using SigmaPlot (Version 2.01 for Windows, Jandel Scientific, Corte Madera, CA). The concentration of soluble protein and ash content data obtained as the pH was decreasing were examined by an analysis of variance and as well as Duncan tests at the different pH values in order to determine any significant difference between temperatures.

RESULTS AND DISCUSSION

Electroacidification Parameters: Duration, Conductivity, and Anode/Cathode Voltage Difference. The analysis of variance of the data (Figures 3 and 7b) indicated that the number of bipolar membranes has a significant effect on the time required to decrease the pH from its initial value of 7.3 to 4.5 ($P < 0.01$), and on the change in anode/cathode voltage difference during the experiment ($P < 0.01$). The number of membranes did not significantly alter the variation in conductivity during electroacidification ($P > 0.05$). The regression lines calculated for the conductivity and voltage as a function of pH produced coefficients of determination ranging from 0.87 to 0.98.

The analysis of variance on the duration of electroacidification, and the changes in voltage and conductivity show that the temperature had a significant effect only on the time required to lower the pH from its initial value of 8.0 to 4.5 ($P < 0.05$). The temperature had no effect on the variations in voltage or current during bipolar membrane electroacidification.

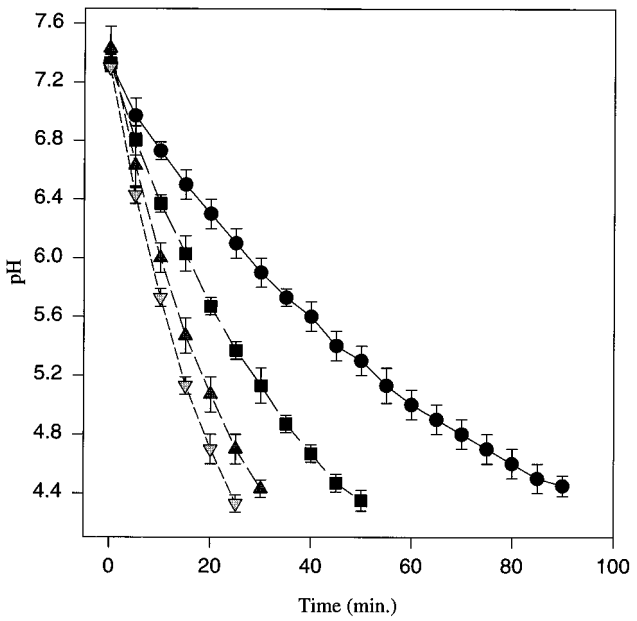

Figure 3. Effect of the number of bipolar membranes, 1 (●), 2 (■), 3 (▲), and 4 (▼), on the time required during decrease of the pH by bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.12 M KCl, run at 20 °C with a 2.5 A constant current.

Electroacidification Time. *Effect of the Number of Bipolar Membranes.* The time required to reach pH 4.5 decreased with increasing number of membranes: 22.1 min for four membranes as opposed to 81.3 min for one membrane (Figure 3). The time required is approximately halved when the number of membranes is doubled ($R^2 = 0.88$). This is due to the increase of membrane surface area on which water dissociation takes place; as the surface is increased the production of H^+ increases. Furthermore, this confirms that the H^+ are generated at the membrane and not at the anode, as occurs in electroacidification with alternating anionic and cationic membranes (Bazinet *et al.*, 1996).

Effect of Temperature. The Duncan test carried out on the time for the pH decrease indicated there was a significant difference between 10 and 20 °C in comparison with 35 °C ($P < 0.05$).

The time required for the pH to decrease from 8.0 to 4.5 at 10 and 20 °C (Figure 4) is similar with 30.4 and 30.2 min, respectively, as confirmed by the Duncan test ($P > 0.19$). On the other hand, the time for the pH to decrease over the same range during electroacidification at 35 °C was 26.8 min, which is significantly different from the results at 10 and 20 °C according to the Duncan test. Increasing the temperature to 35 °C leads to a significant decrease in the time required for the electroacidification procedure.

Conductivity. *Effect of the Number of Bipolar Membranes.* The number of membranes does not affect the conductivity. The conductivity changes in the same way during electroacidification whatever the number of membranes, as indicated by the regression coefficient of 0.55 ($R^2 = 0.92$) calculated on Figure 5. This demonstrates that the electroacidification was carried out under excellent conductivity conditions, and that conductivity does not appear to be a limiting factor in electroacidification.

Effect of Temperature. Initial conductivity values were very different for runs at different temperatures; at 10, 20, and 35 °C the conductivities were 5.85, 8.62, and 10.54 mS/cm, respectively (Figure 6). This confirms the results of Mishra and Bhattacharya (1984) and more

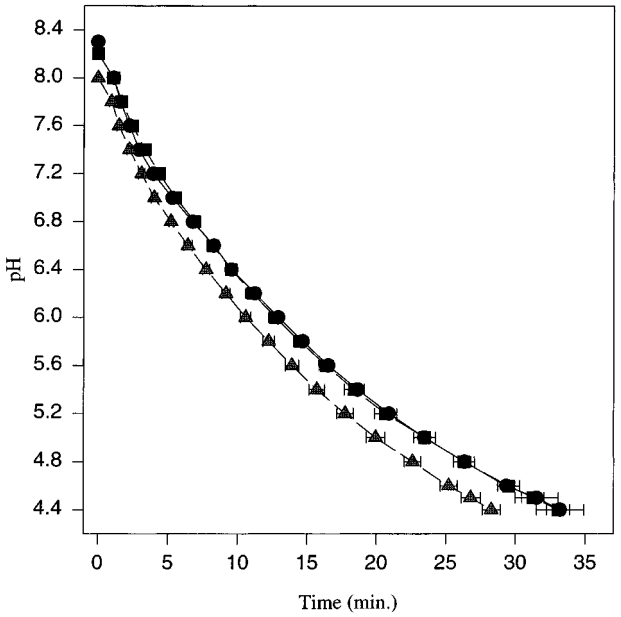

Figure 4. Effect of temperature, 10 °C (●), 20 °C (■), and 35 °C (▲), on the duration of the pH decrease during bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.06 M KCl, run at a 2.5 A constant current.

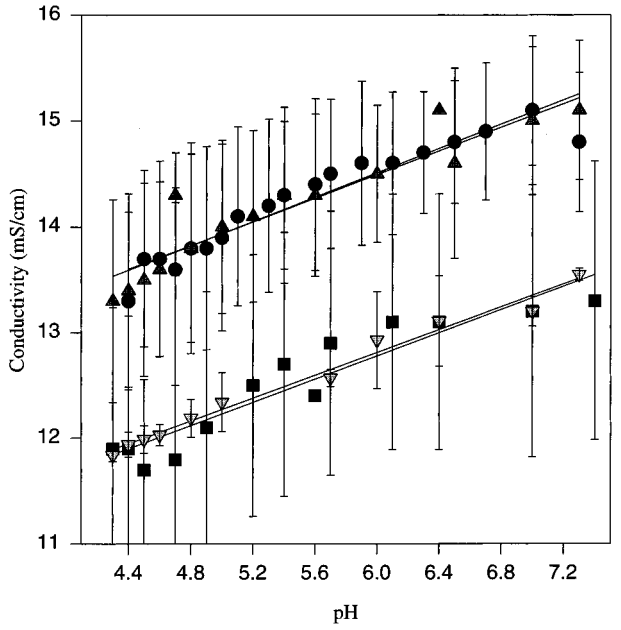

Figure 5. Effect of the number of bipolar membranes, 1 (●), 2 (■), 3 (▲), and 4 (▼), on the conductivity during bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.12 M KCl, run at 20 °C with a 2.5 A constant current.

recently Bazinet *et al.* (1996), who observed that the temperature affects the conductivity of this type of protein solution. By increasing the temperature, the mobility of the ions is increased, while the viscosity of the environment decreases; the temperature increases the ionic dissociation constant, an endothermic phenomenon (Besson, 1967).

As the pH dropped from 8.0 to 4.5 during the procedure, the changes in conductivity are not significant at any of these temperatures. Although the coefficient for the regression lines calculated for the data at 20 and 35 °C is the same, the coefficient for the results at 10 °C is different. The fact that the coefficient is different from the two others is probably related to the greater difficulty in maintaining the temperature

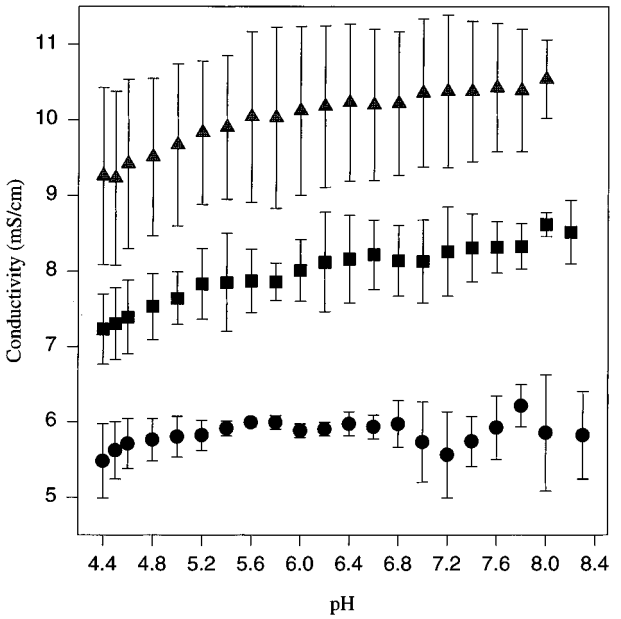

Figure 6. Effect of temperature, 10 °C (●), 20 °C (■), and 35 °C (▲), on the conductivity during the pH decrease of bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.06 M KCl, run at a 2.5 A constant current.

at 10 ± 2 °C as the conductivity is very sensitive to even small variations in temperature.

Anode/Cathode Voltage Difference. *Effect of the Number of Bipolar Membranes.* A greater number of membranes tends to lead to a much larger change in the voltage from the beginning to the end of the run; the voltage variation ranges from 6.3 V with one membrane to 27.0 V with four membranes (Figure 7a). In this case, the change in voltage seems to be proportional to the number of membranes (Figure 7a, $R^2 = 0.90$). The stacking of membranes increases the overall resistance of the cell and consequently the initial voltage value. During the process, when the membranes were stacked, more H^+ and OH^- are generated. Similarly the global ionic exchange decreases the overall resistance of the cell, proportionally to the number of membranes. Therefore the regression coefficients of the lines, calculated for the voltage as a function of pH, are very different, which confirms that voltage change increases with more membranes. The calculated regression coefficients were 2.21 and 9.01 for 1 and 4 membranes, respectively (Figure 7b).

Effect of Temperature. The initial voltage readings decreased as the temperature is increased. Thus at 10, 20, and 35 °C, the voltages at pH 8.0 were 71.6, 45.5, and 42.0 V (Figure 8). This is the result of an increase in the initial conductivity of the protein solution, as previously noted, and which was in turn caused by a lower overall resistance in the system (Bogracheva *et al.*, 1990; Pérez *et al.*, 1994). The H^+, which are generated at the interface of the bipolar membrane, migrate to acidify the protein solution, and then replace mainly the migrated K^+ to ensure the electrical neutrality of the solution. K^+ ions represent 50% of the minerals in SPC (Waggle and Kolar, 1979; Pearson, 1983). The sodium content of SPC is generally low at 0.003% of dry weight. Hence, the contribution of Na^+ migration on the electrical neutrality of the solution is minute compared to K^+. The K^+ migrate into the KCl circuit, concentrating it in K^+ and increasing its conductivity. However, since the H^+ ions are more mobile than the K^+, they will first decrease the resistance of

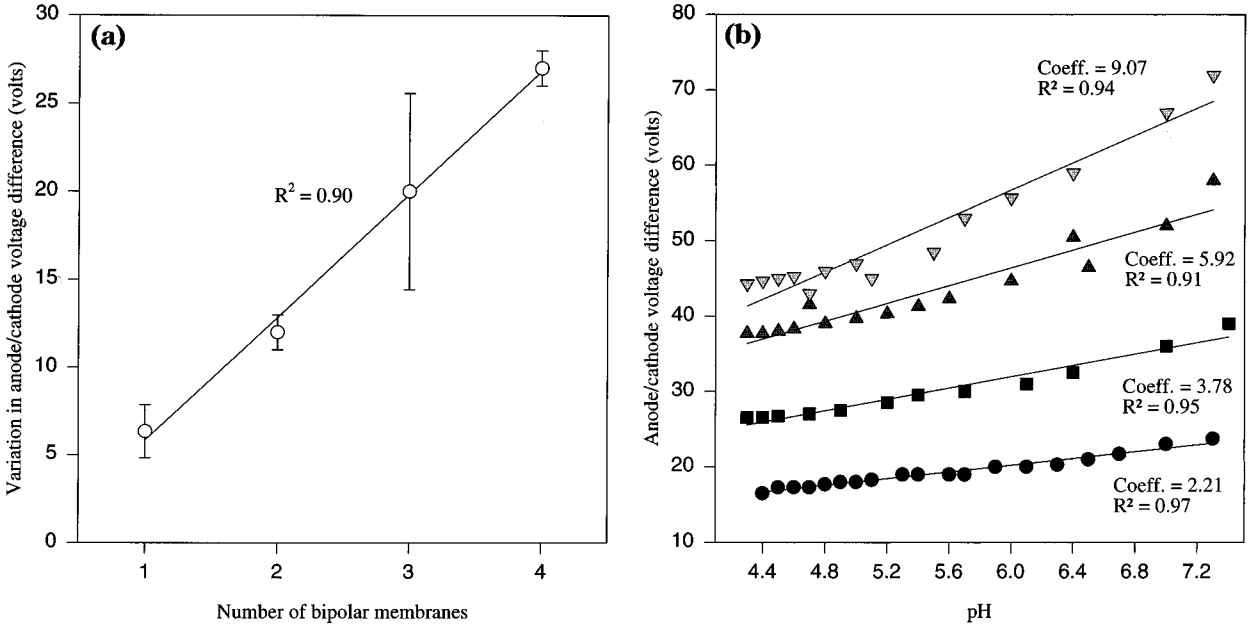

Figure 7. (a) Effect of the number of bipolar membranes on the voltage change observed during bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.12 M KCl, run at 20 °C with a 2.5 A constant current. (b) Effect of the number of bipolar membranes, 1 (●), 2 (■), 3 (▲), and 4 (▼), on the anode/cathode voltage difference during bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.12 M KCl, run at at 20 °C with a 2.5 A constant current.

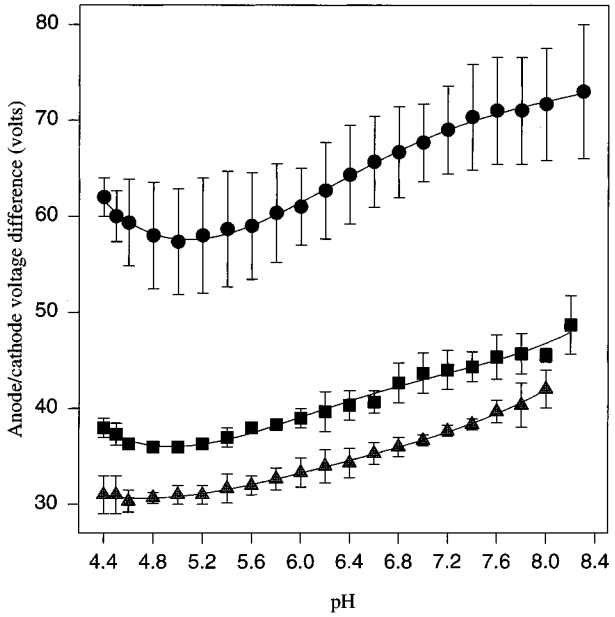

Figure 8. Effect of temperature, 10 °C (●), 20 °C (■) and 35 °C (▲), on the anode/cathode voltage difference during the pH decrease of bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.06 M KCl, run at a 2.5 A constant current.

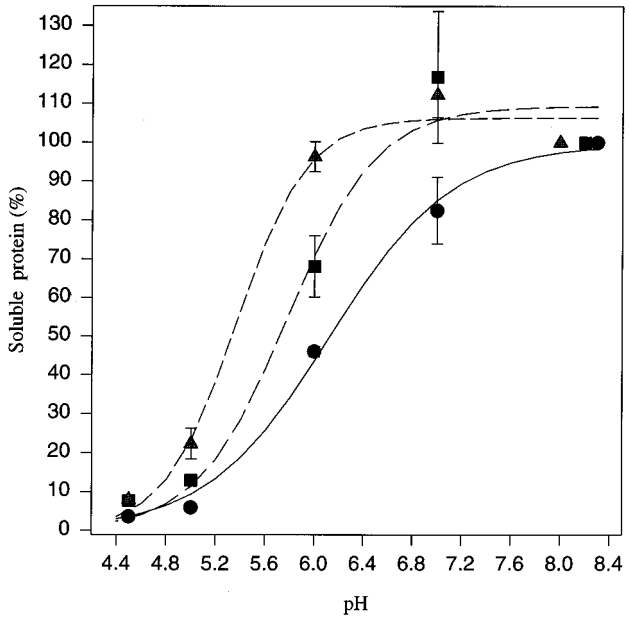

Figure 9. Effect of temperature, 10 °C (●), 20 °C (■), and 35 °C (▲), on the percentage of soluble proteins in the protein solution during bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.06 M KCl, run at a 2.5 A constant current.

the protein solution before contributing to the overall decrease of resistance in the system.

The voltage changes of the solutions as the pH decreases from 8.0 to 4.5 are nevertheless similar for all temperatures: 11.6, 9.6, and 11.0 V at 10, 20, and 35 °C, respectively. These changes, which are related to a decrease in resistance of the system, are the same at all three temperatures, because the quantity of H^+ needed to acidify the protein solution depends solely on the buffering capacity of the system (Cheftel *et al.*, 1985b). Since the protein concentration was the same for runs at all three temperatures, the quantity of H^+ needed was therefore also the same.

Percent Soluble Proteins. The analysis of variance of the soluble protein data indicated that temperature ($P < 0.01$), pH ($P < 0.01$), and the dual interaction of pH and temperature ($P < 0.01$) have a highly significant effect on the percent soluble proteins. Duncan tests performed on the data obtained for different pH values indicated significant differences between runs at different temperatures ($P < 0.01$). The equations of the curves representing the changes in percentage of soluble proteins as a function of the two variables were calculated and modeled (R^2 ranged between 0.97 and 0.99).

During electroacidification, the solubility profiles of the proteins at the three temperatures are different (Figure 9). Thus, at the beginning of the procedure (pH ranging between 8.0 and 8.3), the percent soluble protein is the same: 100%. When the pH dropped to 7.0, at 20 and 35 °C, the percentage of soluble proteins does not change (still around 100%), while at 10 °C, the

percentage has dropped to 82.5%. As the electroacidification continues to pH 6.0, the runs at three different temperatures have very different amounts of soluble protein, respectively 46.1%, 68.1%, and 96.3% for 10, 20, and 35 °C, a trend still evident at pH 5.0 with soluble proteins at 5.9%, 12.9%, and 22.3% for 10, 20, and 35 °C respectively. At pH 4.5, the isoelectric point of soya proteins, runs at 20 and 35 °C have similar percentages of soluble protein, 7.7% and 7.9%, respectively, but significantly higher than that at 10 °C with 3.6%.

Increasing the temperature slows the precipitation of proteins by increasing protein−solvent interactions, which result from decreased hydrophobic interactions (Cheftel *et al.*, 1985a; Kinsella *et al.*, 1985). Evidently, at higher temperature the proteins are rendered insoluble in a narrower pH range. The precipitation occurs between pH 7.6−7.4 and 4.4 at 10 °C; between pH 6.6−6.4 and 4.4 at 20 °C; and between pH 6.2−6.0 and 4.4 at 35 °C. This phenomenon is confirmed by the calculation of the inflection points of the solubility curves: pH 6.12, 5.77, and 5.36 at 10, 20, and 35 °C, respectively. Cheftel *et al.* (1985a) pointed out that in general, for the same pH, the solubility of proteins increases when the temperature increases from 0 to 40−50 °C. The difference in solubility noted at pH 4.5 could be explained by denaturation of the proteins at 10 °C. Cheftel *et al.* (1985a) observed that, at low temperatures, some proteins such as the 11S fraction, aggregate and precipitate at cold temperatures. Proteins which have a high proportion of hydrophobic to polar amino acids, and therefore have structures which depend on hydrophobic interactions, are particularly sensitive to denaturation at the freezing point (Cheftel *et al.*, 1985a). According to Kinsella *et al.* (1985), soya fractions 11S and 7S have relatively high average hydrophobicity values as calculated using Bigelow's equation (1967).

Ash. The analysis of variance of the data shows that temperature ($P < 0.03$) and pH ($P < 0.01$) have a significant effect on the ash content of the protein solutions. However, neither the analysis of variance of the change in percent ash nor the Duncan test and the analysis of variance carried out on the data at each pH value, taken separately, indicated any significant difference between the different temperatures ($P > 0.05$).

As the pH decreased, the ash content (g/100 g of SPC) changed in the same way for all temperatures tested (Figure 10). Thus, the average initial ash content, with all temperature data averaged, would be 20.3%, and would decrease progressively to 19.5%, 18.9%, 17.4%, and reached 16.2% for pH 7.0, 6.0, 5.0, and 4.5, respectively. Furthermore, it should be noted that the ash content decreases exponentially with the pH: from pH 8.2 to 7.0, the ash content decreases by 4%; from pH 7.0 to 6.0 it decreases by 2.65%; from pH 6.0 to 5.0 by 8.3%; and finally from pH 5.0 to 4.5 it decreases by 6.85%.

Increasing the temperature apparently has no effect on the decrease in the ash content during bipolar membrane electroacidification. These data confirm the results obtained from the conductivity and would indicate that only the initial SPC concentration affects the ash content. The quantity of H^+ necessary for precipitation is related to the concentration of proteins present and determines the buffering capacity of the solution. Thus, as the pH decreases, the ash decreases exponentially. This decrease in ash content is probably related to an increase in the number of H^+ which must be produced and transported to reduce successively the pH of the protein solution by one pH unit, since pH is logarithmic. As a result, to obtain electrical neutrality

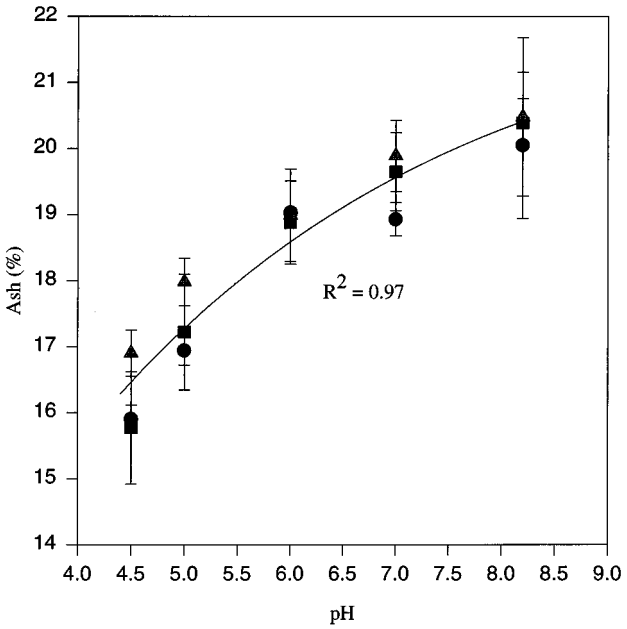

Figure 10. Effect of temperature, 10 °C (●), 20 °C (■), and 35 °C (▲), on the ash content of the protein solution during bipolar membrane electroacidification of a 30 g L^{-1} SPC solution with 0.06 M KCl, run at a 2.5 A constant current.

Table 1. Energy and Power Consumption Calculated for Electroacidification with a Different Number of Bipolar Membranes (One to Four Membranes), Conducted at 2.5 A, of a Protein Solution Containing 30 g L^{-1} of SPC and 0.12 M KCl, Maintained at 20 °C

no. of bipolar membranes	energy (kJ)	average power (kW)
1	237.36	0.0486
2	196.81	0.0756
3	183.13	0.1092
4	188.64	0.1290

in the protein solution, one monovalent cation must cross the cationic membrane for each H^+ ion produced at the bipolar membrane. This decreases the quantity of minerals, and therefore the overall ash content, by desalinization of the protein compartment (Houldsworth, 1980; Chaput, 1979; Brun, 1989).

Energy Efficiency of the Process. *Effect of the Number of Bipolar Membranes.* The energy consumption decreases for an equivalent quantity of proteins to be precipitated, when the number of bipolar membranes is increased (Table 1), due to a better electrical efficiency of the electrodialysis system. With one bipolar membrane, the energy consumption is 237 kJ, decreases to 183 kJ for three membranes, and no further decrease in energy is observed with four membranes. The power consumption increases from 0.0486 to 0.129 kW for an increase from one to four BPMs. The power consumption is higher with four BPMs because the membrane surface available for H^+ production is higher with four BPMs, which results in increased H^+ production.

Doubling the number of membranes decreases, by about one-half, the duration of the electroacidification procedure for a soya protein concentrate of 30 g L^{-1}, in the presence of 0.12 M KCl and at a fixed current of 2.5 A. Increasing the number of BPM in the electrodialysis cell increases the electrical efficiency of the system while decreasing the time required but not in a linear fashion.

Effect of Temperature. Energy consumption decreases with an increase in temperature, dropping from 283 kJ at 10 °C to 133 kJ at 35 °C, a decrease of 53% (Table 2). By relating the energy consumption to the production of one kilogram of isolate, a decrease in the energy

Table 2. Energy and Power Consumption, and Relative Values, at Different Temperatures during Electroacidification with Three Bipolar Membranes (Conducted at 2.5 A) of a Protein Solution Containing 30 g L^{-1} of SPC and 0.06 M KCl

temperature (°C)	energy (kJ)	average power (kW)	relative energy (kWh/kg of isolate)
10	283.32	0.155	0.728
20	176.92	0.097	0.455
30	133.23	0.082	0.371

consumption is noted. A 46.5% decrease in the average power consumption is noted for an increase in temperature from 10 to 35 °C (Table 2). An increase in temperature from 10 to 20 °C and 20 to 35 °C decreases in the relative energy consumption from 0.728 to 0.455 kWh/kg of isolate and from 0.455 to 0.371 kWh/kg, respectively (Table 2).

Increasing the temperature increases the energy efficiency of the electroacidification procedure in a nonlinear fashion. This efficiency increase is lower between 20 and 35 °C than between 10 and 20 °C. This efficiency increase is related to an increase in ion mobility, the result of a decrease in viscosity brought about by the temperature increase (Bourne, 1982). Viscosity and conductivity are important parameters for a protein solution undergoing electrodialysis, because it affects the hydrodynamics of the system. In an electrodialyzer, a high viscosity changes the overall electrical resistance by slowing diffusion and migration of ions in the solution being treated (Bazinet *et al*., 1996).

CONCLUSION

This study demonstrated that electroacidification of soya proteins was related to the generation of H^+ at the surface of BPMs, and that increasing the membrane surface accelerated the electrochemical precipitation quasilinearly while increasing the electrical efficiency. In addition, an increase in the temperature resulted in a decrease in the duration of the process, as well as increase in the energy efficiency.

Optimizing the bipolar membrane electroacidification process would therefore involve using a large membrane surface and operating at room temperature. Processing at room temperature would decrease costs incurred by heating or cooling the solutions without altering the final rate of protein precipitation. For an industrial scale process, the design of the electroacidification cell seems to be one of the important factors to consider for the electrical efficiency of the system.

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