Effect of KCl and Soy Protein Concentrations on the Performance of Bipolar Membrane Electroacidification

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The purpose of this study was to evaluate the effects of various combinations of initial concentrations of soy protein concentrate (SPC) (15, 30, and 60 g/L) and KCl (0.06, 0.12, and 0.24 M) on the efficiency of electroacidification technology. This procedure is derived from electrodialysis. Bipolar membrane electroacidification (BMEA) is based on the production of protons by dissociation of water molecules at the interface of membranes called bipolar membranes. The protons generated by this dissociation are able to migrate toward the cathode and acidify a protein solution. At the end of the process at pH 4.5, BMEA yields a protein precipitation of about 93% of total protein in the electroacidified solution. The SPC concentration is the primary factor in the adjustment of the system to optimum energy efficiency, by its intrinsic potassium content. Added salt affects the performance only at low SPC concentration. Increasing the SPC concentration from 15 to 60g/L and the KCl concentration from 0.06 to 0.24 M decreases the relative energy consumption from 2.82 to 0.49 kW/kg of isolate produced.

Keywords: *Soybean; protein; electroacidification; KCl; bipolar membrane*

INTRODUCTION

A large proportion of the soy protein used in the food industry is in the form of protein isolates. They improve both the nutritional value and the functional properties of food (Visser and Thomas, 1987). They are prepared mainly by an acidic precipitation technique, which involves acidifying a protein solution to its isoelectric point. However, the proteins are sensitive to local excesses of acid, which can lead to a certain amount of denaturation (Kilara and Sharkasi, 1986; Fisher *et al.*, 1986).

In this context we have developed a procedure that precipitates proteins to separate them from other constituents and to concentrate them without denaturation (Bazinet *et al.*, 1996). This procedure is derived from electrodialysis and is called protein electroacidification. Electrodialysis uses an electric field as the driving force and electrically charged membranes as the means of separation. Electrodialysis belongs to a group of membrane separation technologies that are used with increasing frequency in agri-food industries to concentrate, purify, or modify food products (Lopez Leiva, 1988a,b). The low energy consumption, the modular design, and the efficiency and ease of operation of these technologies, as well as the heat sensitivity of many food products, are the bases for this rapid growth. The main uses of electrodialysis in industry currently include demineralization of whey (Houldsworth, 1980; Perez *et al.*, 1994) and cane syrup and green dextrose (Chaput, 1979) as well as the deacidification of fruit juices (Lamarche and Boulet, 1992) and the extraction of tartaric acid from wine (Audinos *et al.*, 1979, 1985). Recently, electrodialysis has been used to extract cytoplasmic proteins from alfalfa (Labrecque *et al.*, 1990), to coagulate whey proteins (Janson and Lewis, 1994), to inhibit the enzymatic browning of apple juice (Tronc *et al.*, 1997), and to reduce disulfide bonds in whey proteins (Bazinet *et al.*, 1997).

The chosen strategy for electroacidification is based on the production of protons by dissociation of water molecules using a sufficiently large cathode/anode voltage difference. The protons generated by this dissociation are able to migrate toward the cathode and acidify a protein solution. These protons can be generated either at the anode or in the outer layer which forms at the interface of ionic membranes or at the interface of membranes called bipolar membranes (Bazinet *et al.*, 1996). Bipolar membranes, a recent technology, are claimed to be the most promising technique for the dissociation of water molecules (Mani, 1991). These membranes are composite and consist of three regions: an anionic and a cationic semipermeable layer and an interface between the two layers. When a direct current is applied, the electron transport across the bipolar membrane is assured by the H^+ and OH^- ions from the dissociation of water in the interface (Mani, 1991).

Various parameters affect the electrical water splitting in an electrodialysis cell and the solubility of protein: ionic strength, flow rate, protein concentration, temperature, etc. (Gardais, 1990; Klein *et al.*, 1987; Kinsella *et al.*, 1985; Cheftel *et al.*, 1985). The purpose of this study is to evaluate the effects of various combinations of initial concentrations of soy protein concentrate (SPC) (15, 30, and 60 g/L) and KCl (0.06, 0.12, and 0.24 M) on the efficiency of electroacidification. The efficiency was evaluated in terms of the energy and power consumed and also the percentage of proteins precipitated. Measuring the ash content of the electroacidified protein led to a better understanding of the overall ionics changes during the process.

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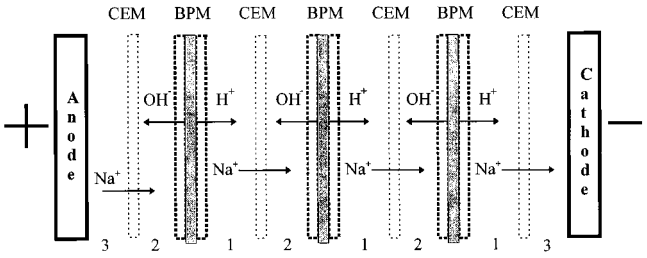

Figure 1. Bipolar membrane electroacidification cell: CEM, cation exchange membrane; BPM, bipolar membrane.

MATERIALS AND METHODS

Material. The crude protein concentrate (60% protein) used in this study was obtained as follows: a given quantity of defatted soy flakes (6 kg) (Central Soya, Woodstock, ON) was added to 9 volumes 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 before being 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 dry matter.

Methods. *(a) Electroacidification Cell.* The module used was an MP type cell (100 cm^2 of effective surface) from the Swedish company ElectroCell purchased from Electrosynthesis Co. Inc. (Model MP Electrocell AB, Lancaster, PA). The cell was assembled as shown in Figure 1. It consists of a structure of eight compartments separated by four CR-64-LMP-401 cationic membranes (Ionics Inc., Watertown, MA) and three Neosepta BP-1 bipolar membranes from Tokuyama Soda Ltd., also purchased from Electrosynthesis Co. Inc. This arrangement defines three circuits containing the protein solution (circuit 1), a 2 g/L aqueous KCl solution (circuit 2), and a 20 g/L Na_2SO_4 solution (circuit 3). 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/m using Filter-Chem flow meters (Model FC-FI-C-3/8, Alhambra, CA). The temperature of the electrolytes was maintained at 20 °C by circulating water inside a stainless steel coil immersed in each of the three reservoirs. The pH of the protein solution was measured with a pH meter (Model Φ11, Beckman Instruments Inc., Fullerton, CA). The anode, a dimensionally stable electrode (DSA), and the cathode, a 316 stainless steel electrode, were supplied with the MP cell.

(b) Protocol. Electroacidification was performed in batch process using a current of 2.5 A, with electrolyte volumes of 6 L. The electroacidification was stopped after the pH reached 4.3, pH 4.5 being the isoelectric point of soybean proteins. The initial pH varied between 7.5 and 7.3.

A 3 × 3 factorial array was set up; three concentrations of SPC (15, 30, and 60 g/L) and three different initial KCl concentrations (0.06, 0.12, and 0.24 M) were tested. Three replicates of each combination of factors were performed in this experiment.

During each treatment, a sample of the protein solution was taken at the following pH readings: initial pH, pH 7, pH 6, pH 5, and pH 4.5. The samples were stored at −40 °C before being lyophilized. The time required to reach pH 4.5 was recorded as well as the anode/cathode voltage difference, and the conductivity of the protein solution as the treatment progressed. Different analyses, such as the concentration of soluble protein and the ash content, were performed to shed light on the electroacidification process.

The power and energy consumption for each treatment were calculated to measure the efficiency of the procedure. The voltage as a function of time multiplied by the intensity of the current was integrated using the following equation:

$$t_x\text{: pH 4.5}$$

$$E = \int I/60 \times U \, dt \qquad (1)$$

$$t_0\text{: pH 7.4}$$

where U = voltage (volts), I = current (amperes), t = time (minutes), and E = energy (joules).

(c) Analysis Methods. (1) 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).

(2) 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}) to measure the conductivity of the protein solutions.

(3) Soluble Protein Concentration. The protein solubility was measured using the Bradford method (1976). The protein solution sample was centrifuged at 10285*g* for 10 min at 20 °C. One hundred microliters of the supernatant, containing 10−100 μg of protein, was added to 5 mL of one-fifth dilution of the dye reagent concentrate (protein assay dye reagent concentrate, 500-0006, Bio-Rad Laboratories Ltd., Mississauga, ON). After vortexing, the absorbance at 595 nm (Beckman spectrophotometer, Model DU 640, Fullerton, CA) was measured after 5 min and before 1 h in 4.5 mL cuvettes against a reagent blank prepared from 0.1 mL of the appropriate buffer and 5 mL of protein reagent. The method was calibrated each time with a BSA standard (protein standard II, 500-0007, Bio-Rad Laboratories Ltd.) from 0 to 1.4 g/L.

(4) Ash Content. Crucibles were washed beforehand in nitric acid (3 N HNO_3), 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 mass recorded. The sample was then ashed at 600 °C for at least 16 h. The sample was cooled in a desiccator and weighed again when it reached room temperature. This method is derived from AOAC Methods 942.05 and 945.39 (AOAC International, 1995).

(d) Statistical Analyses. The data concerning the duration of the procedure, the conductivity, and voltage as a function of time were subjected to an analysis of variance. Regression equations were calculated for the voltage and conductivity as a function of pH using SigmaPlot (version 2.01 for Windows, Jandel Scientific, Corte Madera, CA). The soluble protein concentration as the pH decreased was analyzed by a split-plot analysis of variance, since the Huynh−Feldt condition was met. On the other hand, the ash content as a function of pH was analyzed with a multivariate analysis of variance since the Huynh−Feldt condition was not met. Regression contrasts were calculated for each univariate analysis of variance, using SAS software (SAS, 1989), to examine the effect of interaction between the variables.

RESULTS AND DISCUSSION

Three major electroacidification parameters were measured to evaluate the ionic exchange in the cell: the duration allows us to follow H^+ production at the interface of the bipolar membrane, the voltage indicates the electrical potential difference applied at the electrode of the system, and the conductivity gives information about the ionic exchange in the protein solution. Moreover, the protein concentration and the ash content were measured to evaluate the efficiency of electroacidification for protein precipitation and to follow the overall evolution of ions in the protein solution, respectively.

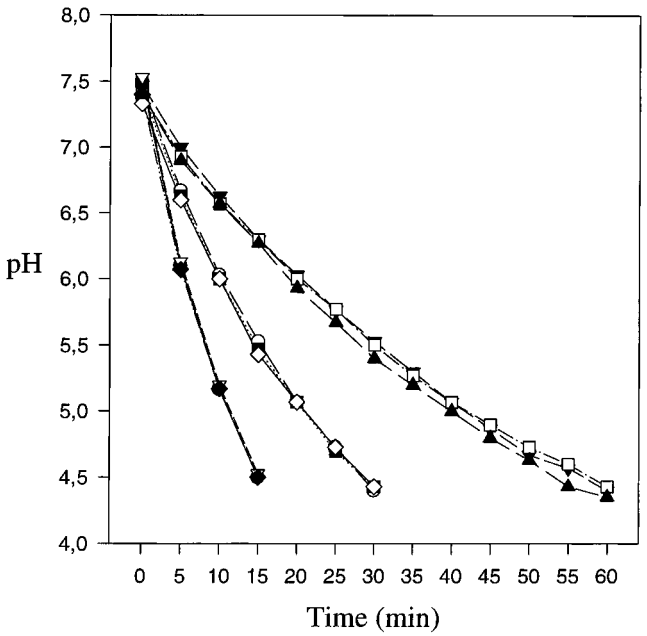

Figure 2. Change in pH as a function of initial concentration of KCl and SPC, during electroacidification run at 20 °C. The different combinations of KCl and SPC concentrations are represented by the following symbols: at 0.06 M KCl, with 15 g/L SPC (●), 30 g/L SPC (○), and 60 g/L SPC (▼); at 0.12 M KCl, with 15 g/L SPC (△), 30 g/L SPC (■), and 60 g/L SPC (□); at 0.24 M KCl, with 15 g/L SPC (◆), 30 g/L SPC (◇), and 60 g/L SPC (▲).

Electroacidification Parameters: Duration, Voltage, and Conductivity. The analysis of variance of the duration of the electroacidification indicated that only the SPC concentration ($P < 0.05$) had a significant effect on the rate of decrease of pH. The analysis of variance of the voltage data showed that the KCl concentration has a highly significant effect ($P < 0.01$), whereas the effect of the SPC concentration on the voltage was only significant as part of a dual interaction with the KCl concentration ($P < 0.05$). The conductivity variation did not appear to be influenced during the experiment by the KCl or SPC concentrations ($P > 0.05$).

The second-order regression curves calculated for the conductivity and voltage as a function of pH produced coefficients of determination on the order of 0.94−0.99.

(a) Duration of Electroacidification. The time required to lower the pH from its initial value of approximately 7.4 to 4.5 is determined primarily by the SPC concentration (Figure 2). With all values of KCl averaged, the time required to reach pH 4.5 appears proportional to the SPC concentration; increasing the SPC concentration from 15 to 30 g/L doubles the time required (14.7 min compared to 27.9 min), as does the change from 30 to 60 g/L (27.9 min compared to 54.9 min). The most plausible explanation would be the larger quantity of H^+ required from the dissociation of water by the bipolar membranes to lower the pH of the solution, which results mostly from the buffering capacity of the proteins in solution. (Cheftel *et al.*, 1985; Prakash and Narasinga, 1990).

(b) Anode/Cathode Voltage Difference. The SPC and KCl concentrations have an agonistic effect on the voltage decrease. As the SPC and KCl concentrations increase, the change in the voltage during electroacidification becomes larger (Figure 3). For the single effect of the KCl concentration, it is interesting to note that it tends to reduce the voltage rise at the end of the experiment, which results from an increase in the overall resistance of the system, thus stabilizing it. This seems to be caused by a larger protein deposit which forms on the spacers at low KCl concentrations. This slight fouling is likely related to the lower solubility of proteins in the absence of salt as the pH decreases (Kinsella *et al.*, 1985; Cheftel *et al.*, 1985).

At low KCl and high SPC concentrations, the rise in voltage at the end of the electroacidification can be explained by a slight fouling on the membrane and by the formation of a protein curd in the interstitial region of the spacers, as observed. This causes an increase in overall resistance in the electrodialysis cell; to maintain the current at a constant level, the voltage increases (Bogracheva *et al.*, 1990; Perez *et al.*, 1994). The time period for electroacidification is not at all affected by this phenomenon as measured from the point where the current can be maintained at a constant value and if continuous dissociation of water at the bipolar membrane is allowed; the production of H^+ is affected only by the current intensity (Mani, 1991).

(c) Conductivity. The SPC and KCl concentrations do not appear to have any effect on the variation of conductivity (Figure 4). If the different starting values of the conductivity are disregarded, which are a function of the number of ions in solution plus the added KCl, the variation of the conductivity between the beginning and the end of the electroacidification is not significant. This is confirmed by the correlation between the conductivity and the pH; the conductivity curves show a weak slope, similar for all KCl and SPC concentrations (Figure 4, $r^2 = 0.94$). This indicates that the electroacidification was indeed performed under the correct conductivity condition. This confirms results obtained by Bazinet *et al.* (1996) on electroacidification of soy proteins using a bipolar membrane.

Soluble Protein Concentration. The analysis of variance of the data shows that the initial SPC ($P < 0.001$) and KCl ($P < 0.001$) concentrations, as well as the pH ($P < 0.001$), have a highly significant effect on the concentration of soluble protein. The effects of these three factors also act in concert doubly and triply. The regression contrast results demonstrate the significant multiple effects of the initial SPC concentration and pH ($P < 0.002$), the KCl concentration and pH ($P < 0.001$), and the SPC and KCl concentration and pH ($P < 0.001$). Except in the triple interaction, there is no interaction between the SPC and KCl concentrations.

(a) Interaction between pH and SPC Concentration. When the inital SPC concentration is increased from 15 to 60 g/L, a change in the soluble protein concentration as a function of pH is observed (Figure 5): at 15 g/L a quasi-linear precipitation occurs, whereas at 60 g/L the protein precipitation curve takes on a sigmoidal form. From initial pH to pH 7.0, no real difference is noted; the percent soluble protein was about 100%. At pH 6, with all KCl concentrations averaged, percent soluble protein measurements of 55.3, 73.9, and 95.5% were obtained for 15, 30, and 60 g/L of SPC. At pH 4.5, the percent soluble protein measurements are fairly similar (all KCl concentrations averaged): 7.7, 6.3, and 7.5%, respectively, for 15, 30, and 60 g/L of SPC.

A high protein concentration slows the electroacidification process as a result of the intrinsic buffering capacity of the protein, which increases with the concentration (Cheftel *et al.*, 1985; Kinsella *et al.*, 1985). However, the final percent soluble protein should not be affected by an increase in the SPC concentration. The variation of precipitation as a function of pH may be

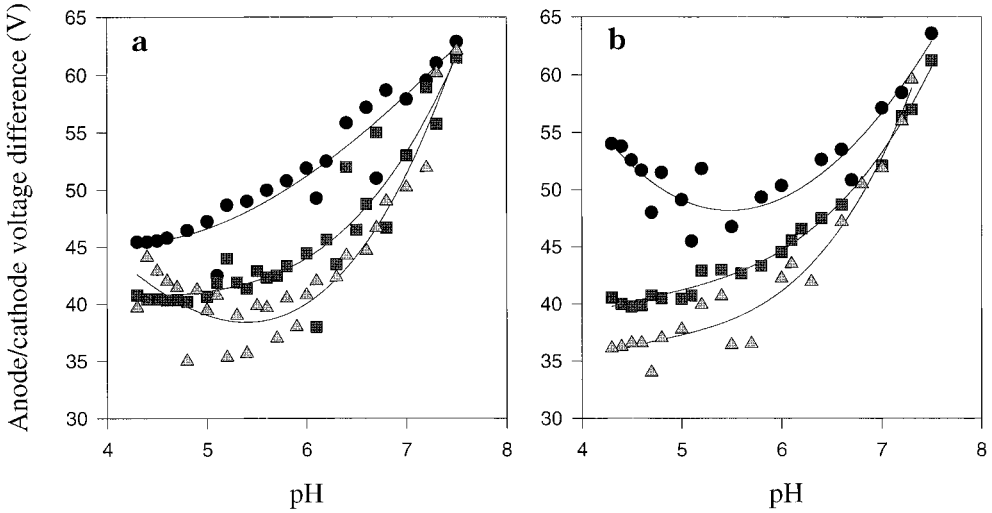

Figure 3. (a) Change in anode/cathode voltage difference during electroacidification run at 20 °C, as a function of initial SPC concentration: 15 g/L (●), 30 g/L (■), and 60 g/L (▲); all KCl concentrations averaged. (b) Change in anode/cathode voltage difference during electroacidification run at 20 °C, as a function of initial KCl concentration: 0.06 M (●), 0.12 M (■), and 0.24 M (▲); all SPC concentrations averaged.

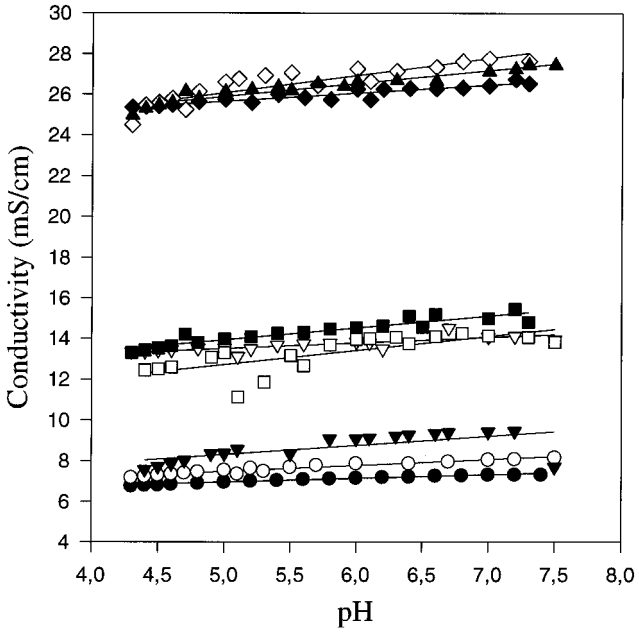

Figure 4. Change in conductivity during electroacidification run at 20 °C, as a function of initial KCl and SPC concentrations. The different combinations of KCl and SPC concentrations are represented by the following symbols: at 0.06 M KCl, with 15 g/L SPC (●), 30 g/L SPC (○), and 60 g/L SPC (▼); at 0.12 M KCl, with 15 g/L SPC (▽), 30 g/L SPC (■), and 60 g/L SPC (□); at 0.24 M KCl, with 15 g/L SPC (◆), 30 g/L SPC (◇), and 60 g/L SPC (▲).

related to the different precipitation profiles of the two principal protein fractions, 7S and 11S. A high protein concentration, up to 4%, should, according to Thanh and Shibasaki (1976), be favorable for the separation of the two globulin fractions. They noted that the β-conglycinin is not very sensitive to increased protein concentration, whereas the precipitation rate of the glycinin increased with a higher protein concentration. This appears to confirm the large change in soluble protein observed for pH 6, a point close to the p*I* of the glycinin and the inflection point of the protein solubility curves (Figure 5).

(b) Interaction between KCl Concentration and pH. When the KCl concentration of the protein solution to be electroacidified is increased from 0.06 to 0.24 M, a large increase in the soluble protein concentration appears (Figure 5). With all SPC concentrations averaged, the sample at the intermediate concentration of 0.12 M KCl has a soluble protein content similar to that of the 0.06 M KCl sample for all pH levels. However, these values have a different evolution from those obtained for 0.24 M KCl: If at pH 7.4 and 7.0 the percent soluble protein concentrations are equivalent, at pH 6.0, 5.0, and 4.5 the precipitation rates are different, but the gap is diminishing. For all KCl concentrations averaged, while the pH is decreasing the percent soluble proteins for 0.06 and 0.24 M KCl are, respectively, 74.1 and 89.3%, 16.4 and 29.7%, and finally 5.3 and 10.8% for the pH values of 6.0, 5.0, and 4.5, respectively. This confirms results obtained by Shen (1976), who noted that at pH 6.8 and with an ionic strength <0.2 M, the solubility of proteins decreases by salting out, whereas at pH 4.7 the solubility increases with the ionic strength by salting in. The increase in percent soluble protein observed at pH 7.0 and 6.0, and at 0.24 M, can be explained by the type of salt used (Kinsella *et al.*, 1985). In contrast to Shen's study (1976), KCl was the salt used in high concentration in these experiments.

(c) Interaction between KCl Concentration, SPC Concentration, and pH. These three variables when coupled have an interaction on the soluble protein concentration. From the initial SPC concentration, the percent soluble protein differs as a function of pH and is influenced by the KCl concentration (Figure 5). At a low SPC concentration, coupled with a low KCl content, the decrease in pH is more or less linear. When the SPC concentration is increased, a latent phase forms at higher pH levels and is accentuated by an increase in the KCl concentration. At pH 6, 7, and 7.4, the effects of increased SPC and KCl concentration combine to increase protein solubility, while at pH 4.5, the isoelectric point of the proteins, only the effect of KCl is noted. At pH 6, 7, and 7.4, the amino and carboxyl groups are charged, but the protein has a net negative charge. When the ionic strength is high, the neutralization of the charge by counterions reduces the electrostatic repulsion, and the solubility therefore is lowered, accentuated by the increase in the SPC concentration. On the other hand, at the isoelectric point, proteins have a

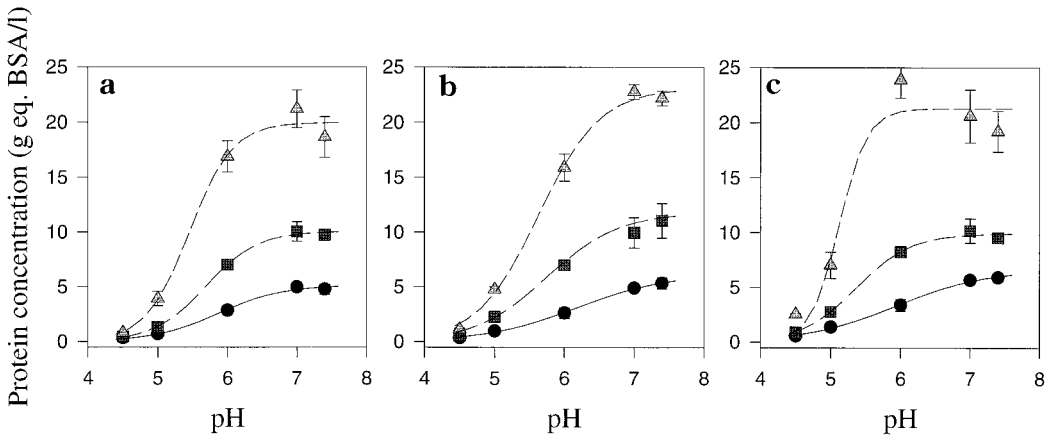

Figure 5. Change in percent soluble protein as a function of pH: initial SPC concentrations are 15 g/L (●), 30 g/L (■), and 60 g/L (▲) and initial KCl concentrations are 0.06 M (a), 0.12 M (b), and 0.24 M (c) during electroacidification run at 20 °C.

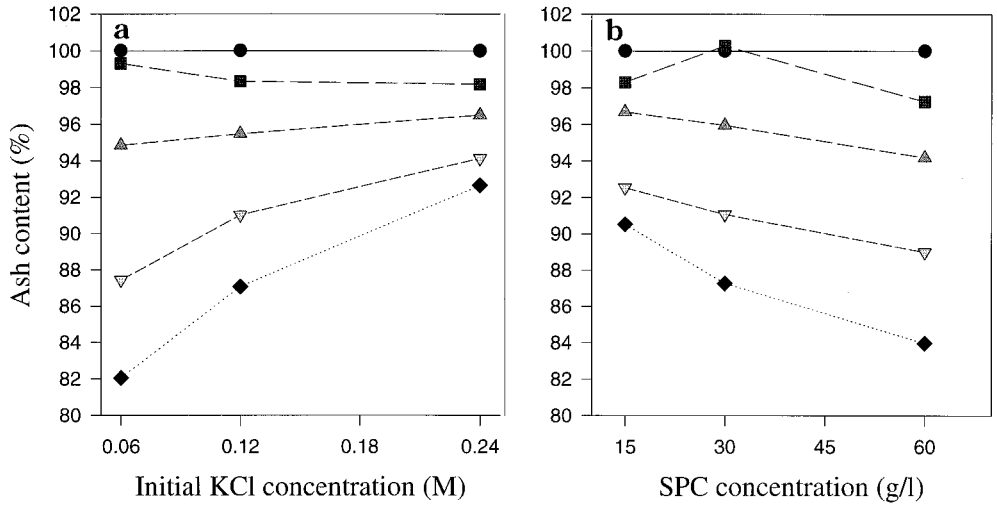

Figure 6. Change in percent ash content as a function of pH and initial KCl concentration (a) and as a function of pH and initial SPC concentration (b) during electroacidification run at 20 °C. pH values: 7.4 (●), 7.0 (■), 6.0 (▲), 5.0 (▼), and 4.5 (◆).

net charge of zero, and the proteins precipitate from hydrophobic interactions. Under these conditions, there are no electrostatic repulsions between molecules. Thus, since the ionic strength of the solution is increased, the salting-in effect of the salt on the hydrophobic interactions progressively dissociates the aggregates and increases the solubility (Kinsella *et al.*, 1985; Cheftel *et al.*, 1985).

Ash Content. The analysis of variance of the data shows the highly significant effect of the initial SPC ($P < 0.0001$) and KCl ($P < 0.0001$) concentrations, as well as the pH, on the ash content of electroacidified proteins. The effects of these three factors are also evident in dual interactions. Furthermore, the regression contrasts indicate that there is a significant effect of the initial SPC concentration and pH ($P < 0.005$) and of the KCl concentration and pH ($P < 0.0001$). There is no interaction between the SPC concentration, the KCl concentration, and the pH ($P > 0.5$).

(a) Single Effect of pH. For all KCl and SPC concentrations averaged, the pH has a cubic effect on the ash content. When the pH decreases, the variation of the ash content varies little between pH 7.4 and 7, decreases rapidly between pH 7 and 5, and slows again between pH 5 and 4.5: the ash content decreases, respectively, from 100 (percent ash initially) to 98.6%, from 98.6 to 90.8%, and from 90.8 to 87.2%. The change in ash content proceeds in a fashion analogous to the change in soluble protein concentration. As we have previously pointed out on the protein solubility curve, the majority of proteins precipitate between pH 7 and 5, reaching a minimum solubility at pH 4.5. As a result, the bulk of the cation migration across the cationic membrane occurs in this pH interval to maintain the electric neutrality of the solution (Gardais, 1990; Houldsworth, 1980).

(b) Interaction between KCl and pH. For the dual interaction between the KCl concentration and pH, it can be noted that the more the added KCl concentration increases, the lower the magnitude of the variation in ash content, for all SPC concentrations: from pH 7.4 to 4.5, the ash content varied from 17.9 to 12.9 to 7.3%, respectively, for 0.06, 0.12, and 0.24 M KCl (Figure 6a).

This variation in ash content can be explained by the effect of salting in of the salts on the proteins. An increase in the salt concentration reduces, to a certain point, the electrostatic attraction between opposite charges on molecules surrounding the proteins, through reactions of ions with the charges on the proteins (Cheftel *et al.*, 1985). Proteins are consequently more liable to react with the H^+ released by dissociation of water and precipitate.

(c) Interaction between SPC Concentration and pH. The interaction between the SPC concentration and the pH was demonstrated by a decrease in the ash content as the electroacidification proceeded. The variation in the ash content increases as the protein concentration increases (Figure 6b): from pH 7.4 to 4.5, variations of

Table 1. Energy and Power Consumption and Relative Values for Different Initial Concentrations of SPC and KCl by Bipolar Membrane Electroacidification Run at 20 °C with a 2.5 A Constant Current

KCl (M)	SPC (g/L)	energy (kJ)	power (kW)	relative energy (kJ/kg of isolate)	relative power (kW/kg of isolate)
0.06	15	129.73	0.147	2497.31	2.829
	30	212.00	0.127	1993.40	1.201
	60	372.21	0.112	1744.40	0.525
0.12	15	103.61	0.116	1985.93	2.231
	30	183.13	0.109	1727.39	1.029
	60	355.46	0.104	1676.40	0.492
0.24	15	105.92	0.119	2106.95	2.374
	30	165.79	0.096	1639.73	0.955
	60	307.25	0.096	1585.94	0.495

9.4, 12.7, and 16.0% were observed for 15, 30, and 60 g/L of SPC, respectively. This variation difference is related to an increase in the number of H^+ to be produced and transported to precipitate the larger quantities of protein when the concentration increases from 15 to 60 g/L. As a result, to maintain the protein solution electrically neutral, one cation must cross the cationic membrane for each H^+ produced at the bipolar membrane. This results in a lower mineral content and, therefore, lower ash content by removing salt from the protein compartment (Houldsworth, 1980; Chaput, 1979; Brun, 1989).

Energy Efficiency of the Process. *(a) Energy Consumption and Relative Energy Consumption.* The energy required rises as the SPC concentration is increased and drops with an increase in the KCl concentration (Table 1). By expressing the energy consumed relative to the production of 1 kg of protein isolate, a drop in energy is observed to accompany an increase in the SPC concentration. In parallel, a drop in energy occurs as the KCl concentration rises. The variation of the energy consumption relative to the increase in KCl from 0.06 to 0.24 M decreases with an increase in the SPC concentration (Table 1). This indicates that the SPC concentration is the primary influence on the energy yield of the bipolar membrane electroacidification cell. At low SPC concentrations, a high level of KCl will improve the overall efficiency of the system.

(b) Power Consumption and Relative Power Consumption. The power data demonstrate the same conclusions noted for the energy consumption in an even more obvious fashion. In fact, the higher the initial SPC and KCl concentrations, the greater the reduction in power consumption (Table 1). The same effect is noted for the relative power: the higher the SPC concentration, the greater the decrease in variation between KCl levels, decreases averaging at 60 g/L (Table 1). The protein level has, therefore, an effect on the energy efficiency of the system, and the KCl concentration intervenes only at low SPC concentrations.

The effect of the SPC concentration is not related to the protein concentration but rather to its intrinsic salt concentration. The proteins have a minor effect on the energy efficiency compared to salts, because the proteins represent a minute proportion of the electrical charges in solution and possess an extremely limited mobility (Bazinet *et al.*, 1996). In fact, the effect of the SPC concentration appears to be related to a high concentration of minerals, approximately 5% of the dry weight of soy protein concentrate (Wolf and Cowan, 1975; Pearson, 1983), of which 50% is potassium (Waggle and Kolar, 1979; Pearson, 1983). At 30 g/L of SPC, the quantity of potassium transported is more or less equivalent to the added material at 0.06 M KCl. Thus, an increase in the salt concentration results in decreased resistance of the medium because the salt transport supplies the ions necessary to maintain the conductivity of the solution during the production of H^+ by the membrane. The resistance of the solutions depends largely on the concentration of electrolytes in the medium (Mishra and Bhattacharya, 1984; Bazinet *et al.*, 1996).

The coupled effect of the SPC and KCl concentrations can be explained together by an increase in the number of charges in solution and by an increase of the solubility of soy proteins, depending on the pH, in the presence of KCl (Bazinet *et al.*, 1996): the mobility and concentration determine the conductivity of the solution. The more the resistance of the system decreases, the more the efficiency of the system increases.

CONCLUSION

We can conclude from the data presented in this study that the KCl and SPC concentrations have an important effect on the performance of bipolar membrane electroacidification. By increasing the SPC concentration (from 15 to 60 g/L) and the KCl concentration (from 0.06 to 0.24 M), the relative power consumption decreases by a factor of 5.7 (from 2.82 to 0.49 kW/kg of isolate produced). Added salt affects the performance only at low SPC concentrations. The SPC concentration is the primary factor in adjusting the system to optimum energy efficiency, by its intrinsic potassium content.

BMEA has specific advantages over the conventional isoelectric precipitation of soy 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. Therefore, BMEA is a green or clean technology. The water consumption is decreased by reusing the effluents generated, and the electrical energy consumption is low. 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).

A study in progress on the changes to K^+ during bipolar membrane electroacidification should provide more information on the role of this ion, which is the major ionic species present in the protein solution.

These results are the basis for a scale-up of the procedure currently under way.

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