Production of Tofu Using Electrocoagulation Technique for Protein Precipitation

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Abstract—**Protein precipitation is a necessary process for a production of tofu. Normally, adding chemical coagulants such as MgCl, $CaSO_4$ and Na_2SO_4 to separate protein from aqueous phase is a traditional method. However, some previous studies reported that consumption of these chemical coagulants for a long term might cause urinary stone disease. In this study, electrocoagulation (EC) was proposed to solve this problem. During this technique, electrical current was applied into the system for changing of the protein surface charge resulting in agglomeration of suspended protein. Since level of voltages and processing time could affect the tofu quality, this research was therefore aimed to study the effects of different voltages at 10, 20 and 30 V and processing times at 30, 60, 90, 120, 150, 180 and 210 min on a percent yield of curd, texture and color of tofu. The comparison between tofu produced by electrocoagulation and commercial tofu in the terms of texture, color and sensory test was also determined to investigate the suitable condition of electrocoagulation for protein precipitation. The results showed that increase in voltage led to higher percent yield of curd. The voltage of 30 V with processing time at 180 min exhibited the highest percent yield of curd (46.24%). It was also observed that color and texture value of tofu produced using electrocoagulation at 30 V for 180 min were not significantly different when compared to that of commercial tofu with the color value of L* (78.00 ± 1.19), a* (0.64 ± 0.07), b* (20.44 ± 0.34) and the total color difference (3.54 ± 0.97) and the textural properties of hardness (5,113.83 ± 15.10 N), springiness (0.87 ± 0.01 s/s) and gumminess (2,697.77 ± 5.26 N). Moreover, sensory evaluation score of tofu produced by EC at 30 V exhibited the highest value when compared to that at 10 and 20 V.**

Index Terms—**coagulant, color, electricity, sensory, soy milk, texture**

I. Introduction

Recently consumer behavior has changed in food choices. Food consumers not only require food safety but also concern about nutrition and healthiness. New products of functional or organic foods for enhancing consumer's health have increasingly been launched. Thus, food processing with non-chemical substance is of interest. Tofu, also known as bean curd, is one of famous healthy foods since it provides low calorie count and high level of protein. Tofu is made by coagulating soy milk with different coagulants such as nigari (MgCl), gypsum ($CaSO_4$) and Na_2SO_4 resulting in soft curd protein and then adding the curd protein into a white block before pressing to get rid of water leading to a firm tofu. Although tofu is claimed to be a healthy food, there have been previous medical studies revealed that regular consumption of tofu for a long term might increase a risk of urinary stone disease since $CaSO_4$ substance was added as a coagulant during tofu processing [1]. Thus an alternative method for tofu production without chemical substance is a challenge.

Electrocoagulation (EC) is a technique of passing electricity through two parallel conductive metal plates to induce ion coagulants for facilitating agglomeration and separating soluble solid from the aqueous phase without adding chemical coagulants [2], [3]. During the EC process, electrolytic reaction of the two metal plates used as anode and cathode occurs. The oxidation reaction at anode and the reduction reaction at cathode generate OH^- and H_2 to reduce surface charge of suspended solid leading to breaking stable emulsion and then precipitation of the suspended solid [4].

EC has not only been widely used in water and wastewater treatment but also been applied in sugar, protein, bioactive compounds and drug to develop separation efficiency. For example, Robic and Miranda [5] successfully developed EC for phenolic and protein precipitation from aqueous solution. Sridhar et al. [6] also found that EC was used for protein precipitation in egg processing. Moreover, their results also showed that the efficiency of the EC depended on many parameters such as levels of current and voltage, processing time, and electrolyte concentration. Since EC involves electrochemical reactions, it can affect the quality of tofu such as its color and texture. Hence, it is important to determine the optimal condition of EC for producing tofu. Sensory evaluation and electrical energy consumption were also conducted for consumer acceptance and determining an operating cost.

II. Materials and Methods

A. Sample Preparation

1kg of soybean was soaked overnight at room temperature and then placed on a screen to get rid of

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water before removing their outer skins. The soybean was blended with 8 liter of water until smooth. The blended mixture was strained using cheesecloth to obtain soy milk. The soy milk was boiled for 20 min and left at room temperature for a further study.

B. Electrocoagulation

Setup of electrocoagulation shown in Fig. 1 consists of two parallel stainless steel plates as electrodes (cathode and anode), DC power supply and a glass container of soy milk. Electrical DC current was applied to across the electrodes with different voltages of 10, 20 and 30 V for 30, 60, 90, 120, 150, 180 and 210 min. The sediment at various treatments were kept and added in rectangular mold. A heavy brick was placed upper the mold to get rid of excess water for 1 h. After that, the weight of each sample was measured.

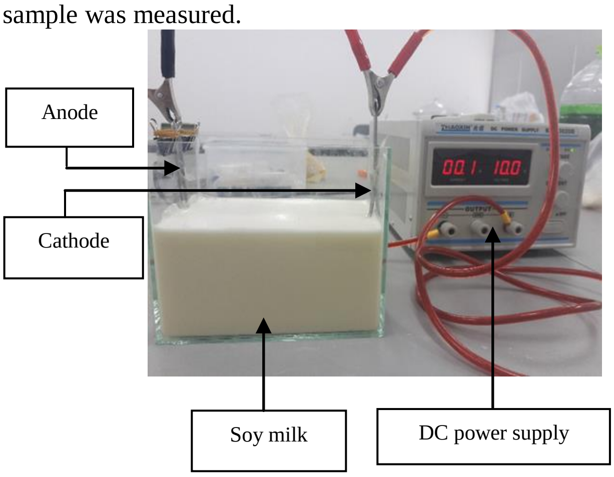

Figure 1. Setup of electrocoagulation

C. Comparison of Tofu Produced by EC and Commercial Tofu

Each tofu produced by different EC voltages and a commercial tofu obtained from a supermarket were determined of color and texture. The color and texture values of each tofu produced by EC were then compared to a commercial tofu to evaluate a suitable EC condition.

D. Color Measurements

Figure 2. Color analysis

Surface color of samples was determined by a spectrophotometer (HunterLab, Mini Scan XE plus, USA) as shown in Fig. 2. The CIE Lab color parameters, i.e., L* (whiteness or brightness), a* (redness or greenness) and b* (yellowness or blueness) coordinates, were used to describe the color of samples. Total color difference (ΔE) was calculated using Equation 1. Color measurements were taken in triplicate.

$$\Delta E = \sqrt{(L^* - L_0)^2 + (a^* - a_0)^2 + (b^* - b_0)^2} \quad (1)$$

where L_0, a_0 and b_0 is whiteness, redness and yellowness of commercial tofu.

E. Texture Analysis

For determining the textural properties of tofu, texture profile analysis (TPA) to all the samples was performed using a Texture Analyzer (TA.XT2i.plus, Stable Microsystems Texture Technologies Inc., UK) as shown in Fig. 3. The texture profile analysis was carried out by two compression cycles between parallel plates performed on cubic samples (1x1x1 inch) using a flat 75 mm diameter plunger, with a 5 s of time between cycles. The parameters that have been used were the following: 0.05N force load cell and 3 mm s^{-1} test speed. The textural properties including hardness, springiness and gumminess were examined.

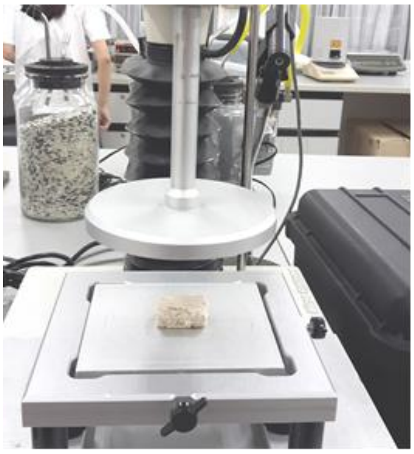

Figure 3. Texture analysis

F. Sensory Evaluation

Sensory evaluation of tofu samples was performed using the 9-point hedonic scale test with the sensory attributes including texture, color, taste and overall acceptability. The panelists consisted to 30 students of Faculty of Engineering and Agro-Industry, Maejo University, Chiang Mai, Thailand.

G. Electrical Enery Consumption

The electrical energy consumption is one of important parameters for determining an operating cost. The electrical energy consumption can be calculated using the following equation [6].

$$E = \frac{VIt}{V_s} \quad (2)$$

where E is the electrical energy (kWh/m^3), V is the cell voltage (V), I is the current (A), V_s is the volume of solution (L) and t is the processing time of electrocoagulation (h)

H. Statistical Analysis

The experiments were designed to be completely random. The presented results are mean of experimental values with standard deviations. The analysis of variance technique and Duncan's multiple range tests were used to determine the significant difference in weight, color and texture of tofu and different treatments at 95% confidence level (P < 0.05). All experiments were performed in triplicate unless specified otherwise.

III. Results and Discussion

A. Weight of Curd at Different EC Treatments

To obtain the highest yield of tofu, a weight of curd at different voltages of 10, 20 and 30 V and various times of 30, 60, 90, 120, 150, 180 and 210 min. As illustrated in Fig. 4, it was observed that longer processing time provided increase in weight of curd and then stable weight of curd after processing time at 180 min. This might be because when electrical current was passed through the two electrodes, electrolysis occurred. During the electrolysis, anode would continuously produce ions into the aqueous system. The released ions could neutralize the charge of protein which is normally negative and subsequently initiate coagulation and precipitation [5], [7]. Thereby, longer processing time increased a chance for neutralizing the charge of protein. However, protein content in soy milk was limited. There was no more protein for coagulation after 180 min.

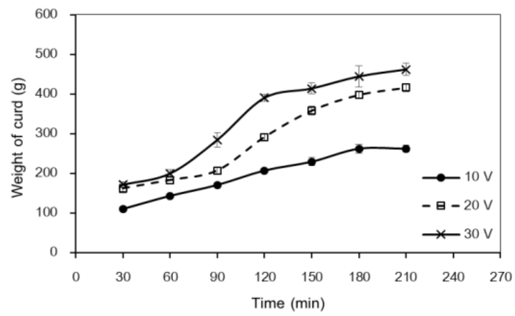

Figure 4. Weight of curd at different voltages and times

Moreover, it can be seen that higher voltage resulted in larger weight of curd. The weight of curd could be transformed to percent yield by dividing the obtained weight of curd by the initial weight of soy milk and multiplying by 100. The results showed that the highest percent yield of curd which was obtained at processing time of 180 min exhibited at the electric potential of 30 V (46.24%) followed by 20 V (41.65%) and 10V (26.25%). Since voltage is the pressure from an electrical power source that pushes charged electrons, the higher voltage was applied, the larger ions was induced leading to the more protein coagulation [8]. The results were agreement with Bazrafshan [9] who reported that a greater precipitate was obtained when increased in electrical potential.

B. Color Measurements

Color of tofu produced using EC at 10, 20 and 30 V for 180 min and commercial tofu were evaluated and presented in Table I. There was no significant difference in whiteness value (L^*) among different voltages and commercial tofu. For the redness (a*) and yellowness (b*) value, tofu produced using EC at 30 V and commercial tofu were not significantly different whereas tofu produced using EC at 10 and 20 V showed significant difference from commercial tofu.

The total color difference (ΔE) which is a combination of the L*, a* and b* values is a colorimetric parameter. This value is used to characterize the variation of color in foods during processing [10]. It was obvious that tofu produced using EC at 30 V exhibited the lowest ΔE value. This indicated that the color of tofu produced by this EC treatment was the most similar to the color of commercial tofu when compared to 10 and 20 V.

TABLE I. Color of Tofu Produced Using EC at Different Voltages and Commercial Tofu

Voltage (V)	L*	a*	b*	ΔE
10	81.12 ±0.52^{a}	0.11 ±0.04^{c}	13.03 ±0.34^{b}	11.71 ±2.95^{a}
20	80.59 ±1.45^{a}	1.93 ±0.10^{a}	11.51 ±0.55^{c}	8.77 ±0.08^{b}
30	78.00 ±1.19^{a}	0.64 ±0.07^{b}	20.44 ±0.34^{a}	3.54 ±0.97^{c}
Commercial Tofu	81.45 ±0.14^{a}	0.66 ±0.02^{b}	20.65 ±0.24^{a}	-

Same letters in the same column indicate that the values are not significantly different (p > 0.05).

Fig. 5 also illustrated color of tofu produced using EC at 10, 20 and 30 V and commercial tofu. It was obvious that color of tofu produced using EC at 30 V and the commercial tofu were more alike than that at 10 and 20 V. This might be because tofu of EC at 30 V contained larger amount yield of curd than that at 10 and 20 V. Mahler and Matter [11] reported that protein concentration could affect color of food products.

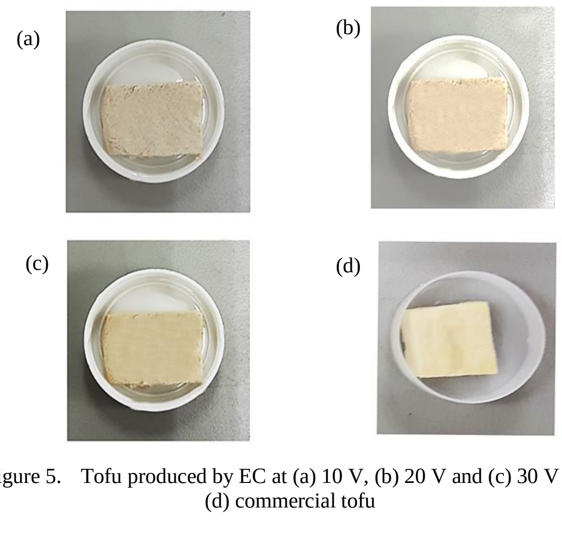

Figure 5. Tofu produced by EC at (a) 10 V, (b) 20 V and (c) 30 V and (d) commercial tofu

C. Texture Analysis

Table II summarized the values of the textural properties in the terms of hardness, springiness and gumminess of tofu produced by EC at 10, 20 and 30 V and commercial tofu. The parameter hardness involves the force performed by mastication that takes part during eating [8]. It was seen that the highest hardness value was obtained in tofu of EC at 30 V. This means that it requires a higher force for the first bite than tofu of EC at 10 and 20 V, respectively. Springiness which is a measure of the recovery in height after the compression during the time that elapses between the end of the first bite and the start of the second bite [12], [13], was highest for the tofu of EC at 30V. It is indicated that tofu of EC at 30 V provided more elasticity than that of EC at 10 and 20 V. Similar results to hardness and springiness value was found in gumminess value. The higher gumminess value was obtained in tofu of EC at 30 V than 10 and 20 V that means that in tofu of EC at 30 V was stickier and more viscid than that of 10 and 20V [14].

Furthermore, comparison of the textural properties of tofu at EC of 10, 20 and 30 V and commercial tofu was considered. The results showed that the textural properties of tofu of EC at 30 V was found to be nearer to the value of commercial tofu than that of 10 and 20 V. This might be due to EC at 30 V provided the highest yield of curd leading to a more firm tofu.

TABLE II. TEXTURAL PROPERTIES OF TOFU PRODUCED USING EC AT DIFFERENT VOLTAGES AND COMMERCIAL TOFU

Voltage (V)	Hardness (N)	Springiness (s/s)	Gumminess (N)
10	1,049.61±2.66^{d}	0.72±0.02^{c}	537.14±1.39^{d}
20	4,924.86±14.48^{c}	0.75±0.01^{c}	2,094.35±4.29^{c}
30	5,113.83±15.10^{b}	0.87±0.01^{b}	2,697.77±5.26^{b}
Commercial Tofu	5,286.23±6.69^{a}	0.95±0.02^{a}	4,206.61±2.37^{a}

Same letters in the same column indicate that the values are not significantly different ($p > 0.05$).

D. Sensory Evaluation

The sensory evaluation score as shown in Table III revealed that there were significant differences ($p<0.05$) between the EC treatments in the terms of color, texture, taste and overall acceptability. It was observed the tofu produced using EC at 30 V was more acceptable by the 30 panelists with the score of 6.83 than that at 10 V (5.66) and 20 V (6.18). Furthermore, the sensory score was consistent with the result of the color and texture analysis that indicated that the characteristic of tofu produced by EC at 30 V was the most similar to the commercial tofu.

TABLE III. MEAN SENSORY SCORE OF TOFU

Voltage (V)	Color	Texture	Taste	Overall acceptability
10	3.51±0.38^{d}	5.24±0.32^{c}	6.14±0.23^{b}	5.66±0.43^{d}
20	6.39±0.72^{c}	6.02±0.22^{b}	6.26±0.55^{b}	6.18±0.15^{c}
30	7.44±0.46^{b}	6.58±0.51^{b}	6.11±0.18^{b}	6.83±0.29^{b}
Commercial Tofu	8.22±0.14^{a}	7.26±0.18^{a}	7.68±0.27^{a}	7.82±0.36^{a}

Same letters in the same column indicate that the values are not significantly different ($p > 0.05$).

E. Electrical Energy Consumption

The electrical energy consumption using EC at 10, 20 and 30 V were presented in Table IV. Higher voltage led to larger electrical energy consumption, as expected. This electrical energy consumption data is important for making industrial investment decision.

TABLE IV. ELECTRICAL ENERGY CONSUMPTION AT DIFFERENT EC VOLTAGES

Voltage (V)	Current (A)	E (kWh/m^3)
10	0.1±0.0^{c}	3±0^{c}
20	0.3±0.1^{b}	18±6^{b}
30	0.5±0.1^{a}	45±9^{a}

Same letters in the same column indicate that the values are not significantly different ($p > 0.05$).

IV. CONCLUSION

This research studied the feasibility of using EC for tofu production. The effects of different EC treatment parameters including voltage and processing time on yield of curd, color and textural properties were performed. The results showed that EC condition at 30 V for 180 min provided the maximum yield of curd. Moreover, tofu produced by EC at 30 V exhibited more similar color and textural properties and sensory score to commercial tofu than that at 10 and 20 V. Under the optimal EC condition of 30 V, the electrical energy consumption was found to be 45 kWh/m^3.

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