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Effects of moisture content on mechanical properties, transparency, and thermal stability of yuba film

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ABSTRACT

Yuba is the skin formed at the surface during the heating of soymilk. The 3rd, 7th, and 11th films were evaluated for properties at different RH. At 39% RH, the 11th film had the lowest moisture, while the 3rd film had the highest moisture. However, at 75% RH, reverse moisture results were obtained. The tensile strengths of the 3rd and 11th films were highest at 15% moisture, whereas the tensile strength of the 7th film was highest at 25% moisture. Elongation of the 3rd (127%) and 11th (85%) films were highest at 25% moisture. The light transmittance of the films was low and opaque at 5% moisture. The films were transparent at 23%–28% moisture, but became opaque as the moisture increased. The films at 39% RH (Δ*H*, 113–203 J/g) had higher thermal stability than those at 87% RH (Δ*H*, 315–493 J/g). Moisture content markedly changed the yuba film properties.

1. Introduction

Yuba or tofu skin is a soy protein-lipid network film that forms on the surface of heated soymilk. Successive films can be lifted from the heated milk and dried for storage (Su & Chang, 2002). As a wrapping for meats and vegetables, dry yuba rehydrates in water and becomes a soft and elastic milky wet film ready for use (Alan, 2008). However, like other soy protein-based films, yuba is fragile in the dry state and has poor moisture barrier properties (Shurtleff & Aoyagi, 2013). Fresh or completely wet yuba is less fragile, but its mechanical properties such as tensile strength are inadequate to wrap and pack food (Chen & Ono, 2010). Many studies have been carried out to optimize yuba processing to increase yield and formation rate (Wang, Swain, Kwolek, & Fehr, 1983), to characterize and improve its appearance in foods (Chen, Yamaguchi, & Ono, 2009), and to improve its mechanical and storage properties (Yuan, Hu, & Yu, 2012). However, the utilization of yuba in non-conventional foods is limited. A potential use could be edible packaging film. Yuba is typically used and studied in the completely wet or dry state. The properties of yuba when between the completely wet and dry states, half-dried yuba (Shurtleff & Aoyagi, 2013), is being studied to develop new applications. The properties of the half-dried phase differ from those of the wet and dry states, and yuba seems to have suitable characteristics for use as edible packaging films. Water is not only the hydrating agent but is also an effective plasticizer that improves the flexibility and mechanical properties of the film (Gontard, Guilbert, & Cuq, 1993). The objective of this study was to evaluate the mechanical properties, transparency, moisture sorption properties, and thermal stability of yuba films obtained at different points of successive skimming and stored at different relative humidities.

2. Materials and methods

2.1. Yuba processing

Yuba films were prepared by using a modified method of Chen et al. (2009). Soymilk was prepared by soaking soybeans with a water ratio of 1:7.5 (concentration of soybean: 8.6%). The boiled soymilk was then transferred to a stainless steel yuba forming pan (15 × 18 × 6 cm) placed in a water bath. The soymilk level was adjusted to 2.3 cm and the temperature of the soymilk was maintained at 85 °C. Successive yuba films were collected at 15 min intervals and labeled sequentially. Eleven sheets of yuba were formed, and the third (Y3), seventh (Y7), and eleventh (Y11) films were chosen for analysis. Yuba was dried (Convection Oven, Cho Sun Science Co., Seoul, Korea) at 60 °C for 120 min, wrapped in plastic film, and stored at −18 °C until use.

2.2. Moisture sorption characteristics

2.2.1. Moisture sorption curve

The dry yuba films (20 × 25 mm) were weighed, and the initial

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moisture content (M_0) was measured using a halogen moisture analyzer (HB43-S, Mettler Toledo, Greifensee, Switzerland). The yuba specimens were then placed in separate desiccators containing saturated salt solutions at 25 °C, and controlled by a hygrometer (Testo 608-H2, Lenzkirch, Germany). The specific relative humidity (RH) of the saturated salt solutions at 25 °C were 39.5% ($CaCl_2$), 57% (NaBr), 75% (NaCl), and 86% (KCl). Deionized water was used to provide 100% RH. The weights of the yuba specimens were measured at intervals of 2 or 4 h until two the consecutive weightings were the same; at this point, it was assumed that an equilibrium condition had been reached. The moisture adsorption curves of yuba were fitted to Peleg (1988).

$$M(t) = M_0 + \frac{t}{k_1 + k_2 t} \quad (1)$$

where M(t) is the moisture after time t, M_0 is the initial moisture, k_1 is the Peleg rate constant (h%$^{-1}$), and k_2 is the Peleg capacity constant (%$^{-1}$).

2.2.2. Sorption isotherm curve

The equilibrium moisture content was calculated from the increase in mass of the dry sample after equilibration at a given relative humidity. The Guggenheim–Anderson–de Boer (GAB) model (Bizot, 1983) was used to fit the soy protein film sorption isotherm data, and the monolayer values for moisture were calculated from the equations.

$$W = \frac{m_0 C k a_w}{(1-k a_w)(1-k a_w + C k a_w)} \quad (2)$$

where W is the moisture content of the material in a dry state, a_w is the water activity, m_0 is the moisture content (d.b) at a monolayer, and C and k are the constants depending on temperature.

2.3. Mechanical properties of yuba

The yuba films were conditioned at a given RH to reach a constant moisture content. A 3 × 6 cm sheet of film was folded three times into 1 × 6 cm. A Compac-100II rheometer (Sun Scientific Co. Ltd., Tokyo, Japan) was used to measure the tensile strength and elongation of the film. The original distance of the strain was set as 4 cm and the moving speed of the table was set as 5 mm/s. Tensile strength and elongation were calculated using the software provided by the manufacturer (Rheology data system 3.0, Tokyo, Japan).

2.4. Transparency

The yuba films (8 × 10 mm) were weighed (w_0) before being soaked in deionized water for 5 min. The remaining water on the surface was gently removed with a kitchen towel. The wet yuba was placed onto the outer side of a spectrophotometer cell (w_c) and the cell was inserted into the spectrophotometer (Ultrospec 2100, GE Healthcare Biosciences Corp., New Jersey, USA). The transmittance was read at 500 nm, the cell was weighed with the film (w_t) at 5 min intervals for 75 min, and an empty spectrophotometer cell was used as the blank. The moisture content M (t) of the film at t min can be expressed as follows:

$$M(t) = \frac{(w_t - w_c) - w_0}{w_t - w_c}$$

where M(t) is the moisture content at time t, w_1 is the weight of the film at 5 min intervals for 75 min, w_c is the weight of the spectrophotometer cell, and w_0 is the initial weight of the film.

2.5. Differential scanning calorimetry

The thermal transition properties of yuba at two different relative humidity were determined using a Seiko SII-EXSTAR 6000-DSC-6200 differential scanning calorimeter (DSC 6200, SII Nano Technology Inc., Tokyo, Japan). The yuba samples of 3.4 mg equilibrated at 39% RH or 87% RH at 25 °C were placed in an aluminum DSC pan. The pan was hermetically sealed and equilibrated at 4 °C for 12 h. The blank was an empty aluminum DSC sealed pan. The thermal transition of yuba was measured by heating from 20 to 275 °C at a rate of 5 °C/min. The onset temperature (T_o), peak temperature (T_p), glass transition temperature (T_g), and denaturation enthalpy (ΔH) were recorded.

2.6. Statistical analysis

Statistical analysis was performed using the software program SPSS 19.0. All data for the analysis of variance (ANOVA) and significance was set at $p < 0.05$. Duncan's multiple range test was applied to determine the significant differences among the mean values. All experiments were performed in triplicate, except for sorption curve equations and DSC.

3. Results and discussion

3.1. Moisture sorption characteristics

3.1.1. Moisture adsorption kinetics of yuba films

As shown in Fig. 1A, all yuba films absorbed moisture rapidly in the first few hours and reached a plateau in less than 10 h at 37% RH and 75% RH but did not plateau until after 20 h at 99% RH; the plateau indicates equilibration has been reached at the specific relative humidity (Cho & Rhee, 2002). Although moisture content was much higher at the higher RH at the start of the rehydration, a longer time was required for the yuba film to reach moisture equilibration when the storage relative humidity was higher. At RH of 99% and 75%, the yuba films that were collected at a later processing time showed higher moisture at equilibrium and reached equilibrium later than the films collected earlier. This may be explained by the higher hydrophobic components (aggregated protein and lipid) in the earlier films and the higher hydrophilic components (carbohydrates) in the later yuba sheets (Wu & Bates, 1972). At was 39% RH, all films reached equilibrium in 10–20 h. Y11 was the last while Y3 was the first to reach equilibrium at 39% RH. Y11 also showed the lowest moisture content at equilibrium, while Y3 showed the highest moisture content and Y7 showed an average moisture content. Data measured from the sorption curve of the yuba films were fitted to Eq. (1), and the sorption curve equations and their constants (k_1 and k_2) were calculated as shown in Table 1. The k_1 values indicate the initial moisture adsorption rate of the yuba film; the higher k_1 value indicates the lower adsorption rate. The k_2 values indicate the moisture content of the film had absorbed when the film reached equilibrium; the higher k_2 value indicates less absorbed moisture (Cho & Rhee, 2002). The coefficients of determination in all cases were very high ($r^2 > 0.99$), indicating excellent fit of the equations to the experimental data. At 75% RH, the moisture isotherm equation k_1 values of the successively collected yuba films increased (5.39, 5.79, and 8.03) from Y3 to Y11, but the k_2 values decreased from 10.62, 8.91, and 6.47 for the Y3 to Y11 samples, respectively. This means that, as the soymilk was heated, the yuba collected earlier absorbed moisture more rapidly in the first few hours, but the maximum moisture content at a given RH (75% or 99%) was lower than the films collected later. However, when stored at 39% RH, both the k_1 and k_2 values of all films increased with the order of collection (k_1 and k_2 values increased from 11.29 to 39.89 and from 18.18 to 47.19, respectively). For the yuba films that were collected later, more time was needed to reach equilibrium, even though they gained the least amount of moisture. The results are consistent with the moisture sorption curves.

3.1.2. Moisture sorption isotherms of yuba films

The moisture adsorption data of the yuba films fitted to the GAB models (Table 2) and isotherms are shown in Fig. 1B. The moisture