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Quality Improvement and Characterization for Production of Acceptable High-Quality Brown Rice Tofu in Japan

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Abstract

The aim of this study was to improve the quality of brown rice tofu to produce it with a superior-quality. When the brown rice flour was heat treated with water, the water absorption rate of flour decreased using brown rice flour with a particle size range of < 212 μm when compared with that of brown rice flour with a particle size range of < 475 μm. The cohesiveness and gumminess of brown rice tofu made from brown rice flour with a particle size range of < 212 μm were fairly high in comparison with those of brown rice tofu made from brown rice flour with a particle size range of < 475 μm. In addition, the adhesiveness and cohesiveness of brown rice tofu remarkably decreased when heating and kneading times of brown rice flour dough were extended. By textural and sensory analyses, it became clear that the use of brown rice flour with a particle size range of < 212 μm and the extension of gelatinization time and heating and kneading times of the dough were important factors for preparation of high-quality brown rice tofu. Therefore, the results indicated that it could produce acceptable high-quality brown rice tofu having smooth and new palate feeling while suppressing adhesiveness and stickiness peculiar to rice flours.

Keywords: brown rice tofu, extention of gelatinization time, extention of heating and kneading times of the dough, flour particle size range, quality improvement

1. Introduction

Food self-sufficiency rate based on calories in Japan for FY2020 is the lowest approximately 37% among 10 developed countries, including Canada, Australia, and America (Ministry of Agriculture, Forestry, and Fisheries, 2020a). It is due to the decrease of rice consumption that is almost 100% self-sufficient and the increase of consumption of livestock products and oils and fats that have high dependence on imports. According to Basic Plan for Food, Agriculture and Rural Areas in Japan for FY2020, it set a national agenda for the increase of self-sufficiency rate based on calories to 45% and of the rate based on production to 75% for FY2030 (Ministry of Agriculture, Forestry, and Fisheries, 2020b). At present, it is considered that the increase of rice consumption is an effective strategy to improve self-sufficiency in food products. However, there is a limit in rice consumption as eating rice because of the decrease of rice consumption year by year. In fact, its consumption is approximately 50.7 kg per person for FY2020 (Ministry of Agriculture, Forestry and Fisheries, 2022b). Therefore, the study on bread (Masure et al., 2016; Nagai et al., 2018a, 2018c; Yano, 2019) and noodle (Nagai et al., 2018b, 2019) processing using rice flour is currently being progressing to expect the increase of rice consumption. In contrast, it is underway to value food cultures such as Japanese traditional foods and local cuisines and to inherit these cultures for coming generations in the diversified eating habits (Ministry of Agriculture, Forestry, and Fisheries, 2022a).

With a view to the expansion of rice consumption for staple food and to the creation and inheritance of new food cultures as a side dish, we were going to focus on sesame tofu, one of vegetarian foods, that is a well-known food in Japan. In addition, we paid attention to brown rice that contains rich nutritional and functional components, such as vitamin B_1, dietary fiber, phytic acid, γ-aminobutyric acid, and γ-oryzanol (Cho & Lim, 2016; Multi Functional Brown Rice Association, 2019). Tamai et al. (2021) tried to prepare brown rice tofu using *kudzu* flour and brown rice flour of nonglutinous rice cultivar *Haenuki* and glutinous rice cultivar *Himenomochi* produced in Yamagata prefecture, Japan. As a result, the doughs made from these brown rice flours became sticky paste when the starches of the doughs were gelatinized under stirring and heating. Particularly, the doughs became creamy sol without gelation, as the rates of rice starches were high in the ingredients. Thus, it revealed that the addition of approximately 12.4% *kudzu* flour as one of main raw material was most appropriate for the production of brown rice tofu using these brown rice flours. Additionally, the doughs made from *Himenomochi* flour had strong stickiness and the gels after solidification were soft when compared with those made from *Haenuki* flour. Therefore, the use of *Himenomochi* flour was unsuitable for the preparation of brown rice tofu (Tamai et al., 2021). Judging from the physicochemical properties and sensory evaluation of brown rice tofu made from these brown rice flours, it elucidated that brown rice tofu made from *Haenuki* flour was expected as one of new '*kawari* tofu'. However, the adhesiveness and stickiness of brown rice tofu made from *Haenuki* flour were fairly high to form the adhesive gels peculiar to rice flour. It is necessary to investigate the preparation condition of brown rice tofu to improve the quality of brown rice tofu. It is considered that the particle sizes of rice flours have an influence on water absorption (Matsuki, 2012) of the dough and adhesiveness of brown rice tofu. In addition, gelatinization time and heating and kneading times of the dough make an effect on the physicochemical property of brown rice tofu, especially smooth texture and sensory characteristics. In the present study, we aimed to prepare brown rice tofu using nonglutinous rice cultivar *Haenuki* flour produced in Yamagata prefecture, Japan changing the preparation conditions (particle size of rice flour, gelatinization time and heating and kneading times of the dough) that differ from the previous paper (Tamai et al., 2021) to establish the method for producing brown rice tofu with the qualities, such as softness, smoothness, and moderate adhesiveness.

2. Materials and Methods

2.1 Materials

Brown rice of nonglutinous rice cultivar *Haenuki* produced in Yamagata prefecture, Japan (grown in 2020, first-class rice), sugar (Mitsui Sugar Co., Ltd., Tokyo, Japan), and salt (Kobe Bussan Co., Ltd., Hyogo, Japan) were purchased from a local supermarket, Yamagata, Japan. *Kudzu* flour was obtained from Hirohachido, Fukuoka, Japan. β-Amylase (14,100 U/g) from soybean and pullulanase (Amano 3, 3,000 U/g) were purchased from Tokyo Chemical Industry Co., Ltd., Tokyo, Japan and Amano Enzyme Inc., Aichi, Japan, respectively. All other chemicals had an analytical grade.

2.2 Preparation of Brown Rice Flour

Brown rice was washed with running water, drained with a sieve, and then dried at 30 ^oC for 6 h using a forced air flow oven (WFO-420, Tokyo Rikakikai Co., Ltd., Tokyo, Japan). Next, these were roasted at 160 to 170 ^oC for 15 min and then cooled at 23 ^oC for 20 min. These were milled for 1 min using a high-speed mill (MS-05, Labonect Co., Ltd., Osaka, Japan), and then the brown rice flour obtained was sieved through a sieve with an opening of 212 μm. These flours with a particle size range of < 212 μm (water content: 6.2±0.20%, damaged starch content: 5.5±0.15%) were vacuum-packed using a vacuum packaging machine (Shinkupackn plus, Wide System Inc., Yamaguchi, Japan) and stored in a cool dark place until use.

2.3 Water Absorption Rate of Brown Rice Flour

A 0.5 g of rice flour (*kudzu* flour) was added to 25 ml of distilled water. After gentle shaking at 30 to 100 ^oC for 30 min using a shaking incubator, these were centrifuged at 1460 × g at 20 ^oC for 30 min. The supernatants were discarded and the residues obtained were weighed. Water absorption rates of the flours were expressed as the rate of water content (ml) absorbed by 1.0 g of flour.

2.4 Preparation of Brown Rice Tofu

Brown rice tofu was prepared by the simmering method. At first, *kudzu* flour was mixed well with half the amount of water to avoid clumping. The suspension was mixed well with brown rice flour that previously mixed with water left, sugar and salt. Next, these were simmered on low heat (160 ^oC) for 14 min for gelatinization and then continued to heat at the same condition for 11 min with kneading and mixing. These were immediately poured into heat-resistant dish (59 mm diameter, 35 mm height) and then cooled at room temperature for 1 h.

These were poured in parallel into stainless steel Petri dish (ST-40, 40 mm diameter, 15 mm height: Yamaden Co., Ltd., Tokyo, Japan) for texture analysis. After solidification, brown rice tofu prepared was vacuum-packed using a vacuum packaging machine and then stored in the refrigerator at 4 ^{o}C for 1 day.

2.5 Characteristics of Brown Rice Tofu

Brown rice tofu was taken out of the refrigerator, and then all the characteristic evaluation of brown rice tofu was performed after 1 h at room temperature.

2.5.1 Color Measurement

Colors of brown rice tofu were measured using a colorimeter (NR-11A, Nippon Denshoku Industries Co., Ltd., Tokyo, Japan) with illuminant 65 calibrated to black and white standards. Color difference (ΔE^*ab) was calculated by following equation.

$$\Delta E^*ab = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (1)$$

Whiteness (W) and metric chroma (C^*) index were also calculated by the following equations, respectively.

$$\text{Whiteness index (W)} = 100 - [(100 - L^*)^2 + a^{*2} + b^{*2}]^{1/2} \quad (2)$$

$$\text{Metric chroma index } (C^*) = (a^{*2} + b^{*2})^{1/2} \quad (3)$$

2.5.2 Gelatinization Degree of Starch

Gelatinization degrees of starches on brown rice tofu were measured by the β-amylase-pullulanase method (Matsunaga & Kainuma, 1981). Gelatinization degrees and decomposition rates of the starches were calculated by the following equations.

$$\text{Gelatinization degree (\%)} = (\text{decomposition rate of sample/decomposition rate of completely gelatinized sample}) \times 100 \quad (4)$$

Where, decomposition rate of sample = [(content of reducing sugar on suspension) – (content of reducing sugar on blank)]/2 × (content of total sugar on suspension); decomposition rate of completely gelatinized sample = [(content of reducing sugar on alkaline gelatinized solution) – (content of reducing sugar on blank)]/2 × (content of total sugar on alkaline gelatinized solution).

$$\text{Decomposition rate (\%)} = (\text{produced reducing sugars/total sugars}) \times 100 \quad (5)$$

Where, produced reducing sugar = (content of reducing sugar on suspension) – (content of reducing sugar on blank); total sugar = 2 × (content of total sugar on suspension).

Total sugars contents and reducing sugars contents were determined by the phenol-sulfuric acid method and the Somogyi-Nelson method, respectively (Aoyagi et al., 2017).

2.5.3 Texture Analysis

Texture analysis of brown rice tofu was performed using a rheometer (TPU-2, Yamaden Co., Ltd., Tokyo, Japan) equipped with a cylindrical plunger No. 56 (20 mm diameter, 8 mm height). Samples prepared in stainless steel Petri dish (ST-40, 40 mm diameter, 15 mm height: Yamaden Co., Ltd., Tokyo, Japan) were compressed twice at a compression speed of 10 mm/s to a clearance of 5 mm. Texture parameters, such as breaking force, adhesiveness, cohesiveness, and gumminess, were obtained from the force-time curve of the texture profile.

2.5.4 Proximate Composition

Proximate compositions of brown rice tofu were investigated as described by Kagawa (2022). Energies were calculated according to the Atwater's calorie factors (Kagawa, 2022).

2.5.5 Sensory Evaluation

Sensory analysis of brown rice tofu was performed in seven-point scale by the panel of thirteen panelists from 19 to 54 years old. The quality characteristics, such as color (brown rice color), flavor (fragrance), smoothness, softness, adhesiveness (difficult-to-stickiness), and overall acceptance, were evaluated.

2.6 Statistical Analysis

Each assay was repeated three times using different samples independently and the results were expressed as mean ± standard deviation. Significant differences were tested by Student's t-test and one-way analysis of variances with the Tukey's Post-Hoc test ($p < 0.05$). Minitab Statistical Software (Minitab 17) was used for statistical analyses.

3. Results and Discussion

3.1 Water Absorption Rates of Different Particle Size Ranges of Brown Rice Flours

It is considered that the quality of brown rice tofu is affected by the water absorption in brown rice flour due to the difference of water absorption in the damaged starch contents and of the particle size ranges of starches. Therefore generally, the water absorption rates of the damaged starches are high (Greer & Stevens, 1959). There was almost no difference of the damaged starch contents between brown rice flour with a prticle size range of < 212 μm (damaged starch content: 5.5±0.15%) and that with a particle size range of < 475 μm (damaged starch content: 5.2±0.06%). It was suggested that there was no difference depending on the damaged starch contents in the water absorption of brown rice flours. Next, the water absorption rates of brown rice flours were measured after heating at 30 to 100 °C for 30 min. As a result, in all cases, the water absorption rates did not increase until 50 °C, however, these rates increased approximately linearly at 50 to 70 °C, suggesting the gelatinization of the starches (Figure 1). Kita et al. (2006) investigated the pasting property of nonglutinous rice cultivar *Akitakomachi* flour produced in Ibaraki prefecture, Japan using a differential scanning calorimeter. It was reported that the gelatinization onset temperature, gelatinization peak temperature, gelatinization conclusion temperature were 57.9, 62.7, and 68.0 °C, respectively. Thus, the swelling of starch granules progress around peak temperature and the swollen starch granules collapses at around 90 °C. The absorption rate of brown rice flour with a particle size range of < 475 μm gently increased above 70 °C and continued to increase at 90 to 100 °C. In contrast, the water absorption rate of brown rice flour with a particle size range of < 212 μm hardly increased at 70 to 90 °C. However, brown rice flour with a particle size range of < 212 μm showed a slight increase of the water absorption rate, although the rate was lower than those of brown rice flour with a particle size range of < 475 μm. In addition, the absorption rate of brown rice flour with a particle size range of < 212 μm were high at 60 to 90 °C.

It is well known that the water absorption of rice flour is different depending on the milling technique of rice, e.g. dry milling and wet milling. Shoji et al. (2012) investigated the hydration property of nonglutinous rice cultivar *Hitomebore* flour produced in Miyagi prefecture, Japan prepared by dry milling. The smaller the particle diameter of rice flour, the higher the starch damage degree and gelatinization degree of the flour and the slower the hydration behavior of the flour. Naganuma (2003) prepared rice flour from *Akitakomachi* produced in Akita prefecture, Japan using jet milling technique and investigated the physicochemical and cooking properties of these flours. As a result, the smaller the particle diameter of rice flour, the starch damage degree and swelling ratio of rice flour increased, resulting in the improvement of water absorption of rice flour. In addition, the pasting properties of rice flours were investigated using a Brabender viscograph. The rice flours with small particle diameter started to gelatinize at low temperature, and the coefficients, such as maximum viscosity, minimum viscosity, and breakdown of rice flours decreased. It indicated rice flours with weak stickiness and adhesiveness. In addition, it was investigated the effect of particle size reduction of rice flour on the property of rice flour gels. The smaller the particle diameter of rice flour, the coefficients of stickiness and adhesiveness of the flour decreased, suggesting the improvement on the texture of rice flour gels. From these investigations, it suggested that brown rice flour with a particle size range of < 212 μm exhibited weak stickiness and adhesiveness due to high proportion of brown rice flour with smaller particle diameter when compared with that with a particle size range of < 475 μm. It was considered that brown rice flour with a particle size range of < 212 μm were hard to absorb water by heating at high temperature due to low water absorption rate at 90-100 °C for 30 min (Figure 1). Additionally, the cereal starches, such as nonglutinous rice starches, partially forms the herical amylose-lipid complex, and the complex does not dissociate by conventional heating and heating using an autoclave. Therefore, rice flour starches do not completely gelatinized (Takeda, 2011). From these reasons, it was considered that the gelatinization degree of the starch on brown rice flour become lower, although brown rice flour with a particle size range of < 212 μm progress the gelatinization of the starches. Moreover, the crystal strucltures of the starches on brown rice flours collapse with gelatinization, however, the water absorption of brown rice flour with a particle size range of < 212 μm do not increase due to rapid passage at approximately 60-70 °C during cooking. Therefore, it suggested that it could produce brown rice tofu suppressing stickiness and adhesiveness.

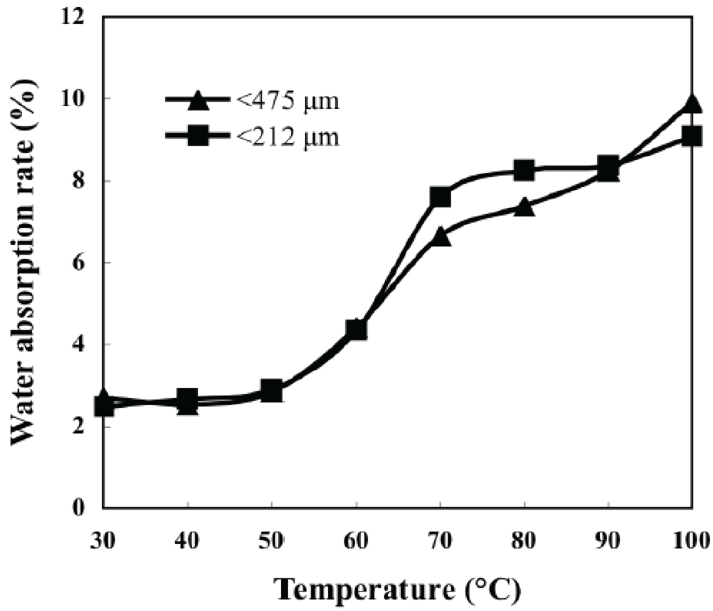

Figure 1. Water absorption rates of different particle size ranges of brown rice flours heated at different temperatures

Note. The water absorption rates of the flours were expressed as the rate of water content (ml) absorbed by 1.0 g of flour.

3.2 Effects of Particle Size Ranges of Brown Rice Flours on the Characteristices of Brown Rice Tofu

Next, brown rice tofu was prepared using brown rice flour with a particle size range of < 212 µm and then investigated the texture characteristics of brown rice tofu. As a result, there was no significant difference in the breaking force and adhesiveness values when compared with brown rice tofu made from brown rice flour with a particle size range of < 474 µm. However, the cohesiveness and gumminess values of brown rice tofu made from brown rice flour with a particle size range of < 212 µm were high in comparison with those of brown rice tofu made from brown rice flour with a particle size range of < 475 µm (Table 1). In addition, the adhesiveness value of brown rice tofu made from brown rice flour with a particle size range of < 212 µm was fairly low when compared with those of commercially available sesame tofu (0.52-1.14 $\times 10^2$ N/m^2) (Tamai et al., 2021).

Table 1. Texture profiles of brown rice tofu made from different particle size ranges of brown rice flours

Particle size range of flour (µm)	Breaking force (hardness) ($\times 10^2$ N/m^2)	Adhesiveness ($\times 10^2$ N/m^2)	Cohesiveness	Gumminess ($\times 10^2$ N/m^2)
< 475	1.07±1.00^a	0.36±4.51^a	0.57±0.04^b	0.63±4.67^b
< 212	1.01±9.45^a	0.35±4.00^a	0.70±0.03^a	0.72±4.36^a

Note. Different letters in the same lane indicate a significant difference ($p < 0.05$).

By sensory analysis, it was evaluated that the adhesiveness value of brown rice tofu made from brown rice flour with a particle size range of < 212 µm was high when compared with that of brown rice tofu made from brown rice flour with a particle size range of < 475 µm. However, these numerical scales were small (Table 2). It was suggested that the use of brown rice flour with a particle size range of < 212 µm was appropriate for the production of brown rice tofu, as brown rice tofu made from brown rice flour with a particle size range of < 212 µm had significantly high scores in the smoothness, softness, and overall acceptance in comparison with that made from brown rice flour with a particle size range of < 475 µm.

Table 2. Sensory evaluation of brown rice tofu made from different particle size ranges of brown rice flours

Particle size range of flour (μm)	Color	Flavor	Smoothness	Softness	Adhesiveness	Overall acceptance
< 475	0.7[a]	1.0[a]	-1.7[b]	-0.3[b]	0.7[a]	-1.7[b]
< 212	0.7[a]	0.0[b]	1.7[a]	1.3[a]	-0.7[b]	1.0[a]

Note. Different letters in the same lane indicate a significant difference ($p < 0.05$).

3.3 Effect of Extension of Gelatinization Time and Heating and Kneading Times of the Dough on the Characteristics of Brown Rice Tofu

Sato et al. (1995) prepared sesame tofu changing the cooking times (15, 25, 35, and 45 min) and the mixing rates (60, 150, 250, and 350 rpm/min) of the dough and investigated these physical properties and microstructures. By textural and creep measurements, it found that hardness and coefficient of elastic modulus of sesame tofu cooked for 25 min were lowest among tested sesame tofu and since then increased with an increase of cooking times, resulting in sesame tofu with firm texture. The amount of evaporation during mixing increased linearly with an increase of cooking times. Particularly, an increase of hardness on sesame tofu for more than 25 min of cooking was greatly influenced by the moisture desorption of sesame tofu with an increase of cooking times. In contrast, it suggested that the mixing rates of the dough have little affect on the hardness of sesame tofu.

Scanning electron microscope observation clarified the existence of nonuniform structures in sesame tofu cooked for 15 min regardless of the mixing rates of the dough. These results indicated that sesame tofu with firm texture was prepared to increase coefficient of elastic modulus on tofu gels when the starch granules remaind ununiformly in sesame tofu gels and the volume fraction of ununiform mass consisting of particulate materials increased. In contrast, it was confirmed that the honeycomb structures consisting of uniform-sized cells were formed in sesame tofu cooked for 25 min. Additionally, the uniform-sized cells in sesame tofu disappeared and the honeycomb structures collapsed to moisture desorption and mixing of the dough for more than 25 min of cooking. By sensory analysis, it was evaluated that the sesame tofu prepared for 25 min of cooking and with mixing rate of 250 rpm/min was favorable in terms of smoothness, taste, and overall acceptance due to having smooth and moderate adhesiveness. In addition, it could be confirmed that it formed the superior uniform-sized cells and honeycomb structures in the sesame tofu. Therefore, it concluded that the cooking time for 25 min and the mixing rate of 250 rpm/min were optimal conditions for the production of sesame tofu.

We tried to investigate the cooking conditions of brown rice tofu preliminarily while referencing these reports (Sato et al., 1995), although we prepare brown rice tofu by hand stirring with the mixing rate of approximately 60 rpm/min. As a result, it was desirable to prepare brown rice tofu as follows: gelatinization time (14 min at 160 ^{o}C) and heating and kneading times (11 min at 160 ^{o}C), respectively. Next, brown rice tofu was prepared using brown rice flour with a particle size range of < 475 μm under these cooking conditions. As a result of the texture analysis, breaking force, adhesiveness, cohesiveness, and gumminess values of brown rice tofu were $1.69 \pm 3.54 \times 10^2$ N/m^2, $0.75 \pm 2.65 \times 10^2$ N/m^2, 0.629 ± 0.03, and $1.06 \pm 2.16 \times 10^2$ N/m^2, respectively. It was revealed that brown rice tofu prepared showed remarkably low adhesiveness and low cohesiveness when compared with that prepared in a short cooking time (Tamai et al., 2021). Murata (1974) investigated the ingredient compositions and the production methods for sesame tofu, and then sesame tofu was prepared using three kinds of methods. As a result, it was reported that the physical properties of sesame tofu changed noticeably by long-term heating and stirring (namely, high heat using gas-fired power for 5 minutes and 30 seconds, and then medium and low heat for 69 minutes and 30 seconds). Particularlly, the kneading of the dough after gelatinization was an important process related to smooth texture of sesame tofu. Thus, it made it possible to prepare brown rice tofu having smooth and suppressing adhesiveness and stickiness peculiar to brown rice flour to extend gelatinization time and heating and kneading times of the dough.

3.4 Characteristics of Brown Rice Tofu Made from Different Amounts of Brown Rice Flours

As described above, brown rice tofu showed high score ($1.69 \pm 3.54 \times 10^2$ N/m^2) in breaking force when the gelatinization time and the heating and kneading times of the dough were extended, resulting in brown rice tofu with firm texture due to moisture desorption. Thus, brown rice tofu was prepared using different amounts of brown rice flours. The formulations and preparation conditions of the brown rice tofu are shown in Table 3. Brown rice tofu E is highly evaluated in our previous report (Tamai et al., 2021). That is, the amounts of flour with a particle size range of < 475 μm and *kudzu* flour are large to the amount of water added. In contrast, product F is prepared using only *kudzu* flour. Additionally, these products are prepared in relatively short gelatinization time (7 min at 160 °C) and kneading time (3 min without heating). The physicochemical properties of brown rice tofu A-D are shown in Table 4.

3.4.1 Color

Color characteristics of brown rice tofu were investigated. As a result, brown rice tofu A-D exhibited significantly lower *L** and *b** values when compared with brown rice tofu E (Table 4). Except for brown rice tofu A, *a** values of brown rice tofu B-D were remarkably low in comparison with that of brown rice tofu E. In addditon, *a** and *b** values of brown rice tofu significantly decreased with decreasing the amount of brown rice flours added (Table 4). Clear differences were found in color among the brown rice tofu tested. Brown rice tofu A as well as E had vivid colors with high degree of yellowness. However, the lower the amount of brown rice flour added, the lower the metric chroma of brown rice tofu, resulting in brown rice tofu with dull color. Next, whiteness indexes of brown rice tofu were calculated. Brown rice tofu C and D showed significantly high indexes when compared with brown rice tofu E. On the contrary, there was little difference on whiteness indexes between brown rice tofu A and B. Thus, a difference was found in the brownness degree among the brown rice tofu tested. The ΔE^*ab values of brown rice tofu A-D were calculated to brown rice tofu E. As a result, color differences were evaluated as follows: A (appreciable), B and C (much), and D (very much), respectively (Table 4). It revealed that there was remarkable difference on color difference among these tested brown rice tofu and color difference of brown rice tofu increased with decreasing the amount of brown rice flour added. It was suggested that the color of brown rice tofu (including browning) was strongly influenced by the amount of brown rice flours added and cooking condition of the dough, such as the gelatinization time and heating and kneading times of the dough.

Table 3. Ingredient composition and preparation conditions for improved brown rice tofu

Ingredients	A	B	C	D	E*	F*
Roasted *Haenuki* flour (g)	40.0	30.0	20.0	10.0	48.2	-
Kudzu flour (g)	40.0	40.0	40.0	40.0	48.2	96.4
Sugar (g)	30.0	30.0	30.0	30.0	48.2	48.2
Salt (g)	1.0	1.0	1.0	1.0	0.6	0.6
Water (g)	450.0	450.0	450.0	450.0	450.0	450.0
Preparation conditions						
Particle size range of flour (μm)	< 212	< 212	< 212	< 212	< 475	< 475
Heating temperature for gelatinization (°C)	160	160	160	160	160	160
Heating time for gelatinization (min)	14	14	14	14	7	7
Heating temperature for kneading and mixing (°C)	160	160	160	160	Without heating	Without heating
Heating time for kneading and mixing (min)	11	11	11	11	3	3

Note. *The ingredient compositions and preparation conditions were quoted from our previous paper (Tamai et al., 2021).

3.4.2 Gelatinization Degree of Starch

The gelatinization degrees of starches on brown rice tofu were measured. As a result, the degrees (approximately 96.8-97.9%) of brown rice tofu (A-D) were slightly high when compared with that (approximately 94.7%) of brown rice tofu E (Table 4). However, no significant difference was found among the brown rice tofu tested. In addition, there was no significant difference in the decomposition rates (approximately 67.7-69.6%) among brown rice tofu A-D and E.

3.4.3 Textural Property

The textural properties of brown rice tofu were investigated. As a result, the breaking force of brown rice tofu A (1.32×10^2 N/m^2) was significantly high in comparison with that of brown rice tofu E (1.11×10^2 N/m^2), suggesting that brown rice tofu A was harder than brown rice tofu E (Table 4). In contrast, brown rice tofu B (1.01×10^2 N/m^2) showed lower breaking force when compared with brown rice tofu E. Particularlly, the breaking forces of brown rice tofu C (0.73×10^2 N/m^2) and D (0.71×10^2 N/m^2) were significantly low approximately two-thirds of that of brown rice tofu E, suggesting brown rice tofu with soft texture. The adhesiveness of brown rice tofu A (0.68×10^2 N/m^2) and B (0.35×10^2 N/m^2) were significantly low approximately a half and one-third of that of brown rice tofu E (1.23×10^2 N/m^2), respectively. In addition, brown rice tofu C (0.22 × 10^2 N/m^2) and D (0.17 × 10^2 N/m^2) had a remarkably low levels of adhesiveness at approximately from one-sixth to one-eight of brown rice tofu E.

The adhesiveness of brown rice tofu decreased linearly with decrease of the addition of brown rice flour added (R^2 = 0.8715). Thus, brown rice tofu A-D were the tofu having less stickiness due to significant decrease in adhesiveness, although brown rice tofu E exhibited significantly high adhesiveness and strong stickiness. The cohesiveness value is the internal binding force between components that form the brown rice tofu. That is, the value means the fragility on the tissues of brown rice tofu. The cohesiveness values of brown rice tofu were approximately 0.56-0.66, indicating that these were well-organized brown rice tofu with low elasticity, although brown rice tofu C showed slightly low cohesiveness when compared with brown rice tofu A, B, and D.

Table 4. Physicochemical properties of improved brown rice tofu

	A	B	C	D	E*	F*
Color *L**	66.6±0.09^c	66.6±0.25^c	66.8±0.11^c	66.4±0.08^c	69.5±0.50^b	77.8±0.23^a
*a**	1.66±0.16^a	0.18±0.05^c	-0.36±0.12^d	-2.28±0.16^f	1.10±0.03^b	-0.90±0.01^e
*b**	15.2±0.19^b	11.5±0.13^c	8.44±0.28^d	-0.81±0.08^f	19.4±0.17^a	1.30±0.17^e
Color difference (Δ*E***ab*)	Appreciable	Much	Much	Very much	-	Very much
Metric chroma (*C**)	15.25^b	11.49^c	8.44^d	2.42^e	19.39^a	1.58^e
Whiteness (W)	63.28^c	64.71^{bc}	65.72^b	66.35^b	63.82^c	77.74^a
Gelatinization degree (%)	96.8±6.92^a	97.4±2.83^a	97.4±6.28^a	97.9±6.13^a	94.7±1.92^{ab}	92.9±7.25^b
Decomposition rate (%)	69.6±4.24^b	69.6±3.18^b	69.5±4.75^b	69.5±3.61^b	67.7±8.12^b	77.7±7.64^a
Texture parameters						
Breaking force (hardness) (× 10^2 N/m^2)	1.32±5.03^a	1.01±9.45^c	0.73±3.79^d	0.71±1.15^d	1.11±2.89^b	1.31±2.89^a
Adhesiveness (× 10^2 N/m^2)	0.68±9.10^b	0.35±4.00^d	0.22±4.33^e	0.17±3.46^e	1.23±0.00^a	0.48±3.82^c
Cohesiveness	0.73±0.01^a	0.71±0.03^a	0.55±0.04^b	0.73±0.03^a	0.81±0.04^a	0.62±0.03^b
Gumminess (× 10^2 N/m^2)	0.96±3.70^a	0.72±4.36^b	0.40±1.15^d	0.52±3.06^c	0.90±6.81^a	0.81±2.61^{ab}

Note. *Data was quoted from our previous paper (Tamai et al., 2021). Different letters in the same row indicate a significant difference ($p < 0.05$).

The gumminess represents pasty property of foods and means the energy to chew the semi-solid foods into smaller pieces so it becomes soft enough to swallow (Szczesniak, 1963). Brown rice tofu A (0.96 × 10^2 N/m^2) showed the same gumminess as brown rice tofu E (0.90 × 10^2 N/m^2). However, the gumminess of brown rice tofu B-D (0.40-0.72 × 10^2 N/m^2) were significantly low when compared with that of brown rice tofu E, indicating that these were brown rice tofu with low sticky texture and good feeling to the throat. It was considered that it could suppress the adhesiveness and stickiness peculiar to brown rice flour on brown rice tofu prepared in the present study, although it was suggested the increase of stickiness of brown rice tofu and its gel surface with increasing of the amount of brown rice flour added. It might be interesting to investigate the relationship between the physicochemical properties of brown rice tofu and these structures in future.

3.4.4 Sensory Quality

Sensory evaluation of brown rice tofu was performed. Brown rice tofu A had color with higher score as well as brown rice tofu E (Figure 2). In contrast, the color scores of brown rice tofu C and D were low. These results reflected metric chroma index of brown rice tofu (Table 4). It was suggested that the color characteristics of brown rice tofu were influenced by the amount of brown rice flour added and the boiling condition of the dough, such as extension of gelatinization time and heating and kneading times of the dough. Flavor score of brown rice tofu E was the highest due to a large amount of brown rice flour added (Figure 2). These scores dropped to a lower score, depending on the rates of brown rice flour in ingredient composition. In contrast, the tendencies in opposition to flavor scores were observed in terms of smoothness. That is, brown rice tofu D showed the highest score in terms of smoothness, followed by brown rice tofu C, B, and A (Figure 2). The lowest score was shown in brown rice tofu E that the amount of brown rice flour added was largest. In addtion to extension of gelatinization time and heating and kneading times of the dough, it tended to increase smoothness scores of brown rice tofu with the decrease of the amounts of raw material powders added, especially brown rice flour. These results indicated that brown rice tofu C and D were the tofu with smoother sensory properties among the brown rice tofu tested. Therefore, it was considered that an increase of the water content ratio based on the weight of raw material powders made significant impacts on not only the molecular structures and properties of the starches of *kudzu* flour and brown rice flours but also physical property of brown rice tofu, such as feeling on the tongue and smoothness. Brown rice tofu D exhibited the highest score in softness, followed by brown rice tofu C (Figure 2). No significant difference was found between brown rice tofu A and B in softness index.

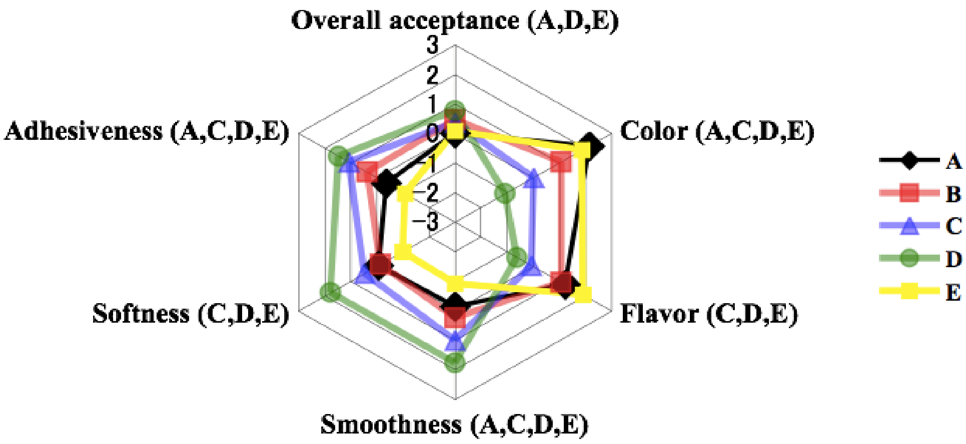

Figure 2. Sensory evaluation of improved brown rice tofu prepared in different ingredient compositions

Note. The sensory qualities of improved brown rice tofu were evaluated on the basis of color, flavor, smoothness, softness, adhesiveness, and overall acceptance. Significant difference at $p < 0.05$ indicates between brown rice tofu B and the samples in parentheses. A: roasted *Haenuki* flour 40.0 g + *kudzu* flour 40.0 g, B: roasted *Haenuki* flour 30.0 g + *kudzu* flour 40.0 g, C: roasted *Haenuki* flour 20.0 g + *kudzu* flour 40.0 g, D: roasted *Haenuki* flour 10.0 g + *kudzu* flour 40.0 g, E: roasted *Haenuki* flour 48.2 g + *kudzu* flour 48.2 g.

In contrast, brown rice tofu E showed the lowest score in softness among the brown rice tofu tested, suggesting hardest brown rice tofu. It suggested that softness of brown rice tofu depended on raw material powders ratio based on the weight of the amount of water added. The adhesiveness scores of brown rice tofu showed the same tendencies as the smoothness scores (Figure 2). That is, these tendencies supported the results of the texture analysis, such as breaking force and adhesiveness (Table 4). Finally, the overall acceptance of brown rice tofu was observed. Brown rice tofu D was overall favorable, followed by brown rice tofu B and C (Figure 2). In contrast, brown rice tofu A had low score as well as brown rice tofu E that the amount of brown rice flour added was largest and the gelatinization time of the dough was short. In addition, it was evaluated that brown rice tofu had unique textures, such as pudding and jelly. From these investigations, it was considered that brown rice tofu prepared had a potential for brown rice tofu having smooth and new palate feeling while suppressing adhesiveness and stickiness peculiar to brown rice flour.

3.4.5 Proximate Composition

From these results, it was concluded that brown rice tofu B could be produced as a brown rice tofu with good textural properties and sensory acceptability in consideration of the usage of brown rice flour. The proximate composition of brown rice tofu B was investigated. As a result, crude protein contents, crude lipid contents, and carbohydrate contents were remarkably low when compared with those of brown rice tofu E (Table 5). Therefore, the energies of brown rice tofu B were low. In contrast, water content of brown rice tofu B was significantly high, suggesting the tofu had a high-water content. It is considered that water contents are associated with not only the physicochemical properties and sensory qualities of brown rice tofu but also the preservation of tofu. No significant differences were found in crude ash contents and salt contents between brown rice tofu B and E.

In the present study, we tried to improve the quality of brown rice tofu, focusing on the particle size range of brown rice flour. Yamamoto (1985) divided potato starch into quarters with a certain particle size range and then evaluated the pasting properties of these starches and the physical properties of gels made from these starches. As a result of the amylograph analysis using 4% starch suspension, the larger the particle size range of the starch, the higher the maximum viscosity (peak viscosity) and the lower the peak temperature of the gelatinized starch, resulting in large breakdown. That is, it suggested that the starch showed strong stickiness. In addition, the solubility of the starch increases with an increase of particle size range of the starch. The larger the particle size range of the starch, it is easy to gelatinize the starches and to collapse the swollen starch granules. The coefficients for the dynamic viscosity modulus and dynamic elasticity modulus of starch paste liquid were high when the starch with smaller particle size range was used by dynamic viscoelasticity measurement. It is known that the dynamic viscoelasticity of starch paste liquid is associated with its sensory property. The starch paste liquid with low coefficients of these moduli shows stickiness when compared with that with high coefficients of these moduli. Thus, the starch paste liquid with smaller particle size range is not sticky.

Table 5. Proximate compositions of brown rice tofu B and E

	B	E*
Energy (kcal/100 g)	70.7^{b}	122.0^{a}
Water (g/100 g)	82.2 ± 0.80^{a}	75.9 ± 0.20^{b}
Crude proteins (g/100 g)	0.2 ± 0.43^{b}	0.6 ± 0.12^{a}
Crude lipids (g/100 g)	0.03 ± 0.01^{b}	0.08 ± 0.01^{a}
Carbohydrates (g/100 g)	17.4 ± 0.83^{b}	29.8 ± 1.85^{a}
Crude ashes (g/100 g)	0.21 ± 0.01^{a}	0.25 ± 0.04^{a}
Salts (g/100 g)	0.21^{a}	0.17^{a}

Note. *Data was quoted from our previous paper (Tamai et al., 2021). Different letters in the same row indicate a significant difference ($p < 0.05$).

In addition, the coefficient of the dynamic Young's modulus, namely the elasticity modulus, is low and that of the breaking strain is high on the starch gels with larger particle size range in comparison with those with smaller particle size range. Furthermore, the breaking force of the gel made from the starch with smaller particle size range is high. It shows that it could form sofy and stretchy gel when the starch with larger particle size range is used. That is, the starch gel made from the starch with smaller particle size range is harder than that made from the starch with larger particle size range. However, the coefficients of the dynamic viscosity modulus and dynamic elasticity modulus decrease with increase of heating temperatures and heating times. Therefore, it suggests that the extension of gelatinization time and heating and kneading times of the dough is an effective method for the preparation of brown rice tofu with soft texture. In addition, it is considered that it could prepare brown rice tofu with weak stickiness and adhesiveness using brown rice flour with smaller particle size range.

From our research, it revealed that the use of brown rice flour with particle size range of < 212 μm to improve the water absorption of the dough when it was heat-treated and the extension of gelatinization time and heating and kneading times of the dough were important factors for preparation of high-quality brown rice tofu. Thus, it could produce acceptable high-quality brown rice tofu having smooth and new palate feeling while suppressing adhesiveness and stickiness peculiar to brown rice flour.

4. Conclusion

In summary, brown rice tofu was prepared using nonglutinous rice cultivar *Haenuki* flour produced in Yamagata prefecture, Japan changing the preparation conditions of our previous report to establish the method of producing high-quality brown rice tofu. The water absorption of the dough was improved to use brown rice flour with a particle size range of < 212 μm. In addition, it could dramatically improve the quality of brown rice tofu to extend gelatinization time and heating and kneading times of the dough. From the results of textural analysis and sensory evaluation, the optimal ingredient compositions for the production of brown rice tofu were 30 g of roasted brown rice flour, 40 g of *kudzu* flour, 30 g of sugar, 1 g of salt, and 450 g of water, respectively. The optimal gelatinization time and heating and kneading times of the dough were 14 min at 160 ^{o}C and 11 min at the same temperature, respectively. Thus, we made it possible to produce high-quality brown rice tofu with acceptable attributes by partially changing the ingredient composition.

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