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# Impact of heat-moisture treatment applied to brown rice flour on the quality and digestibility characteristics of Korean rice cake

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**Abstract** Effect of heat-moisture treatment (HMT) of brown rice flour on the quality and digestibility of Korean rice cake (*jeolpyeon*) was investigated. Brown rice flour with 20% moisture content was heat-moisture treated at 100–110 °C for 1–2 h, and subsequently cooled to 4 °C for 1–2 h. The lightness of HMT rice cake decreased as HMT temperature and time increased, whereas redness and yellowness increased. The hardness, springiness, and cohesiveness of HMT rice cake were much lower than those of brown rice cake. HMT of rice cake caused an increase in the resistant starch content and a decrease in the rapidly digestible starch content. In sensory evaluation, hardness of HMT rice cake was substantially lower than that of rice cake made with untreated brown rice due to retardation of retrogradation. However, the overall acceptability of HMT rice cake was lower than that of white rice cake or brown rice cake.

**Keywords** Rice cake · *Jeolpyeon* · Heat-moisture treatment · In vitro digestibility · Textural properties · Sensory evaluation

## Introduction

Rice (*Oryza sativa* L.) has been used as a major food source in Asian countries, including Korea. Brown rice (BR) is a whole grain, consisting of 5–6% bran, 2–3% embryo, and 92% endosperm [1] and it is rich in dietary fiber, phytic acid, vitamins, gamma-amino butyric acid (GABA), and minerals. Rice cake (*Tteok*) is a traditional Korean food product made with rice flour [2]. Many kinds of rice cakes can be made depending on the manufacturing method, including steaming rice cake, battering rice cake, boiled rice cake, and supporting rice cake [2]. Herein, *Jeolpyeon* is a kind of steaming rice cake made with non-waxy rice flour dough.

The main component of rice is starch, which could be classified into a rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) according to its digestibility [3, 4]. RDS increases the blood sugar rapidly after consumption, and SDS is digested more slowly throughout the entirety of the small intestine. RS has been shown to reduce a high level of cholesterol and inhibit fat accumulation as it is not digested by gut microbiota in the small intestine [5].

Heat-moisture treatment (HMT) is a hydrothermal treatment that physically alters the physicochemical properties of starch by causing changes in its molecular structure [3]. The HMT process involves incubating starch at a low moisture content (typically $\leq$35%) for a certain time period (15 min–16 h) below the gelatinization temperature (84–120 °C) [5]. Numerous studies have been conducted to assess the effects of HMT on the structure and physicochemical properties of cereal, tuber, and legume starches [3, 5–7]. HMT of starches improves the thermal stability and reduces the retrogradation as compared to those of native starches [7]. These properties of HMT starch can be utilized in starch-based products such as fried batter foods, noodles, frozen foods and biodegradable films [6, 8].

The effects of HMT on various properties of rice starch have been reported by several researchers [6, 9], whereas little work has been done on properties of HMT rice flour

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[8, 10]. Commercial rice flour is produced by dry or wet milling of white polished rice, whereas rice starch is obtained by the alkaline steeping method involving multi-stage purification. Direct application of the HMT process to rice flour may have an economic advantage for utilization of the rice-based products by improving their quality. Arns et al. [8] reported that HMT in grain reduced the extraction yield of starch and enhanced the mechanical and thermal stability of rice starches. Chung et al. [11] observed that application of the HMT process to germinated brown rice modified the pasting properties of rice flour and the noodles made from the flour containing HMT germinated brown rice showed improved cooking and textural qualities. Walter et al. [12] reported that the thermal treatment of rice improved its milling quality, nutrient availability, sensory properties and resistant starch content. However, no information is available on the effect of HMT directly applied to brown rice flour on the digestibility and quality of the rice-based product. Therefore, the aim of this study was to evaluate the digestibility and quality characteristics of Korean rice cakes made with HMT brown rice flour.

## Materials and methods

### Materials

Non-waxy brown rice (*Japonica type*, *Dasan*) harvested in Korea in 2014 was provided by the National Institute of Crop Science, Rural Development Administration (Suwon, Korea). The rice grain was dehulled and brown rice flour was prepared by wet-milling. The brown rice was soaked in distilled water (10 times the weight of rice) at 25 °C for 4 h, drained, and then milled into flour using a cyclone mill (1093 Cyclotec Sample Mill, Foss Tecator, Hoganas, Sweden). The rice flour was dried to an approximate 10% moisture content in an air oven at 40 °C, and then stored at 4 °C for further treatment.

### Heat-moisture treatment of brown rice

Brown rice (BR) flour was weighed into a glass container and allowed to reach a 20% moisture content. The container containing rice flour with 20% moisture content was sealed, thermally treated in an air oven at 100 and 110 °C for 1 or 2 h, and subsequently cooled at 4 °C for 1 or 2 h. This heating and cooling process was repeated three times. Upon opening the containers, the rice flour was air-dried to attain a uniform moisture content (~10%) and then screened by passing through a 75 mesh sieve.

### Pasting properties of rice flour

Pasting properties of the heat-moisture treated brown rice flour were analyzed using a Rapid Visco-analyser (RVA-TecMaster, Newport Scientific Ltd., Warriewood, Australia). The rice flour (7% w/w, 30 g of total weight) was mixed with deionized water in the RVA canister. The sample was held at 50 °C for 1 min, heated to 95 °C in 6 min, held at 95 °C for 5 min, cooled to 50 °C for 6 min, and held at 50 °C for 2 min. Pasting temperature, peak viscosity, breakdown, setback, and final viscosity were obtained from RVA viscograms.

### Preparation of rice cake

*Jeolpyeon*, the Korean traditional rice cake, was prepared using either white rice flour, brown rice flour, or HMT brown rice flour (300 g) as well as water (240 g) and salt (3 g). Salt and water were added to the rice flour and all materials were evenly mixed, followed by steaming for 20 min. The cooked rice cake was cooled to room temperature and kneaded for 5 min using a kneader (Model KMM020, Kenwood Ltd., Hertfordshire, UK). The rice cake was tightly packed in plastic wrap.

### Color properties of rice flour and rice cake

Color properties of flours and rice cakes were determined using a colorimeter (Spectra magic NX, Konica Minolta, Tokyo, Japan). The CIE color values were recorded as $L^*$ (lightness), $a^*$ (redness), and $b^*$ (yellowness).

### Texture properties of rice cake

Textural analysis of the rice cake was performed using a Texture Analyzer (TA-XT+, Stable Micro Systems, Surrey, UK). For textural measurements, the rice cake sample was cut into pieces of 20 × 20 × 20 mm and a two-bite test was performed using a cylindrical plunger (20 mm diameter). The test speed of the probe was 1.0 mm/s and the deformation was set at 50% of the original height. From the force-distance curve of the texture profile, textural parameters including hardness, adhesiveness, cohesiveness, springiness, gumminess, and chewiness were obtained.

### In vitro digestibility of rice flour and rice cake

In vitro digestibility of both rice flour and rice cake was determined according to the method described by Englyst et al. [13] with some modification. For rice cake analysis, the rice cake was passed through a meat mincer (diameter, 4 mm) to simulate human mastication. The minced rice cake sample was used for further digestion analysis. The minced rice cake sample (1.0 g) or rice flour (0.5 g), 10 mL of guar gum solution (5 g/L in 0.05 M HCl), pepsin (0.05 g), and five glass balls (15 mm) were added to the sample tubes, and then incubated in a shaking water bath (150 rpm) at 37 °C for 30 min. Sodium acetate buffer (0.5 M, pH 5.2), pancreatic α-amylase (P-7545, Sigma–Aldrich, St. Louis, MO, USA), and glucoamylase (A-9913, Sigma–Aldrich) were added to the sample tubes, followed by incubation in a shaking water bath (150 rpm) at 37 °C for 180 min. After incubation, aliquots (0.5 mL) were taken at intervals and added to 4 mL ethanol (80%), and the sample was centrifuged at 2000 rpm for 10 min. The glucose content released at each time point of the supernatant was measured using a glucose oxidase–peroxidase (GOPOD) kit. Rapidly digestible starch (RDS) content was measured after incubation for 20 min, slowly digestible starch (SDS) was the starch that was hydrolyzed between 20 min and 120 min, and resistant starch (RS) was the starch that remained undigested after 120 min incubation.

### Sensory evaluation of the rice cake

A descriptive sensory panel consisting of 15 panelists who were graduate students at the Department of Food Science and Nutrition of Chonnam National University participated the sensory evaluation. The age of panelists ranged from 20 to 30 years, which would minimize the effect of age on the identification capability. Sensory parameters including color, flavor, and hardness were evaluated by the quantitative descriptive test focused on attribute scoring from 1 (low intensity) to 7 (high intensity). Sensory attributes comprised color (lighter–darker), flavor (poor flavor–pronounced flavor), and hardness (soft–rough). In order to determine the overall consumer acceptability of rice cakes, a seven-point hedonic scale (1 indicated dislike extremely, 4 indicated neither like nor dislike, and 7 indicated like extremely) was used. The samples offered were 3 cm in size. After each evaluation, the panelists rinsed their mouth with water and waited for at least 5 min before the next test.

### Statistical analysis

The results were reported as means of triplicate measurements. Statistical analyses was performed with Duncan's multiple range test ($p < 0.05$) of significance using an SPSS software system (Version 21, SPSS Institute Inc., Cary, NC, USA).

## Results and discussion

### Pasting properties of rice flour

Pasting properties of brown rice flour (F-BR) and heat-moisture treated brown rice flour (F-HMT) as determined by a Rapid Visco-analyzer (RVA) are presented in Table 1. Pasting temperature of rice flour increased during HMT, but the peak viscosity and breakdown decreased during HMT (Table 1), indicating that the starch granules slowly swelled up and the degradation of these swollen granules was retarded by HMT. The extent of these increases and decreases became more pronounced with an increase in heating time as well as in temperature. These changes can be attributed to the association between chains of the starch granule in the amorphous region and the crystalline region during the applied high temperature and moisture [14]. Chung et al. [11] suggested that HMT could generate a protective shell around the exterior of partially gelatinized starch granules, which could act as a barrier to water penetration and inhibit subsequent gelatinization and pasting. Arns et al. [8] found that HMT applied to rice grains increased the pasting temperature and decreased the peak viscosity, and they claimed that these changes could be attributed to the strengthening of links and an increased molecular binding force between starch chains. Zavareze and Dias [15] suggested that the HMT-induced decrease in breakdown indicated increased mechanical and thermal stability of starches by promoting the strengthening of interactions between amylose and amylopectin molecules. Puncha-arnon and Uttapap [6] found that the effect of HMT on pasting viscosity was more pronounced in rice flour than in rice starch since the protein in rice flour would undergo alteration by HMT along with the starch granules. Denaturation of rice proteins in rice flour by HMT results in an increase in their surface hydrophobicities, which would retard the swelling of HMT starch granules in flour [6]. Consequently, the protein in HMT flour played an important role, resulting in a lower pasting viscosity during HMT.

There was also a significant reduction in setback and final viscosity upon HMT of brown rice flour and the extent of decrease was more pronounced as the treatment time and temperature increased (Table 1). During cooling of the starch paste, leached amylose molecules rapidly aggregate, leading to the formation of amylose junction zones which contribute to the setback and final viscosity [16]. Chung et al. [5] reported that HMT reduced the amylose leaching in starch granules by promoting additional amylose–amylose and amylose–amylopectin chain interactions, thereby causing reduction in the setback and final viscosity. Putseys et al. [17] suggested that straight chain lipids, which are present in whole rice grains, could interact to form inclusion complexes with helical formation of amylose molecules. These inclusion complexes with the helical conformation of amylose molecules and the lipid molecules can restrict the mobility of amylose by steric hindrance for amylose double helix formation [8]. A longer heating time and a higher heating temperature could thus

**Table 1** Pasting and color properties of heat-moisture treated brown rice flours

| Rice flour | Pasting properties | | | | | Color properties | | |
|---|---|---|---|---|---|---|---|---|
| | Pasting temperature (°C) | Peak viscosity (cP) | Breakdown (cP) | Setback (cP) | Final viscosity (cP) | $L^*$ | $a^*$ | $b^*$ |
| F-BR | $87.5 \pm 0.2^c$ | $662 \pm 9^a$ | $255 \pm 3^a$ | $892 \pm 11^a$ | $1298 \pm 4^a$ | $85.96 \pm 0.01^b$ | $0.72 \pm 0.01^d$ | $10.95 \pm 0.03^d$ |
| F-HMT1 | $88.1 \pm 0.2^b$ | $331 \pm 14^b$ | $1 \pm 1^b$ | $546 \pm 151^b$ | $726 \pm 45^b$ | $86.45 \pm 0.24^a$ | $1.08 \pm 0.04^c$ | $11.96 \pm 0.29^c$ |
| F-HMT2 | $88.3 \pm 0.0^b$ | $238 \pm 6^c$ | $0 \pm 1^b$ | $250 \pm 11^c$ | $488 \pm 16^c$ | $78.71 \pm 0.14^d$ | $4.35 \pm 0.03^b$ | $19.57 \pm 0.12^b$ |
| F-HMT3 | $90.2 \pm 0.2^a$ | $124 \pm 3^d$ | $1 \pm 1^b$ | $183 \pm 7^c$ | $307 \pm 5^d$ | $79.02 \pm 0.04^c$ | $5.36 \pm 0.02^a$ | $20.84 \pm 0.08^a$ |

F-BR, brown rice flour; F-HMT1, BR flour heated at 100 °C for 1 h and cooled at 4 °C for 1 h; F-HMT2, BR flour heated at 100 °C for 2 h, cooled at 4 °C for 2 h; F-HMT3, BR flour heated at 110 °C for 2 h, cooled at 4 °C for 2 h

Values followed by the different superscripts in the same column are significantly different ($p < 0.05$)

induce more lipid–amylose complexes and strong interactions between starch chains, leading to decreased retrogradation. Consequently, HMT of brown rice flour may induce an increase in heat and shear stability of the starch paste and a decrease in granule swelling and amylose leaching. As the pasting behavior is practically useful in predicting the properties of starch-based food products, HMT brown rice flour could be utilized to promote favorable changes in the quality of the prepared rice cake.

## Color properties of rice flour

Color values of BR flour (F-BR) and HMT-BR flour (F-HMT) are shown in Table 1. HMT of brown rice flour significantly affected the color values. HMT resulted in a decrease in lightness ($L^*$) and increases in redness ($a^*$) and yellowness ($b^*$). The darkening effect induced by HMT was more pronounced as the treatment time and temperature increased. Similarly, Bian and Chung [18], and Takahashi et al. [19] reported that the lightness of rice flour was decreased and the redness and yellowness were increased by HMT. The darkening effect during HMT could be mainly due to the Maillard reaction between amino groups in protein and reducing sugars in starch [9, 14].

## In vitro digestibility of rice flour

The amounts of the rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) in rice flour are presented in Table 2. The RDS, SDS, and RS levels were highly dependent on the HMT conditions. HMT increased the RDS and RS contents and decreased the SDS content in native rice flours. The increase in RDS content with HMT could be attributed to the disruption of double helices in the starch crystallites at the granule surface and to crystallite reorientation. The increase in RS content with HMT may be due to the increase in starch chain interactions [5]. However, the RDS content decreased, but the SDS and RS contents increased as heating temperature and time of HMT increased (Table 2). For example, the RDS content for HMT1 (100 °C, 1 h), HMT2 (100 °C, 2 h), and HMT3 (110 °C, 2 h) was 63.1, 55.2, and 48.3%, respectively (Table 2). These results could be due to enhanced starch chain mobility with increase in heating temperature and time, which could lead to decreased enzyme susceptibility.

Upon heating the rice flour in excess water, the molecular hydrogen bonds between starch chains are disrupted and the starch structure is transformed to a continuous amorphous structure, which would enable increased enzyme accessibility. It is for this reason that the cooked rice flour exhibited a substantially increased RDS content and a decreased SDS content (Table 3). A decrease in RDS content and increases in SDS and RS contents were also observed with HMT. These changes were more pronounced as the HMT time and temperature increased (Table 2). Similar results were reported by Chung et al. [5] for gelatinized corn, pea, and lentil starches and they claimed that the increases in SDS and RS contents with HMT after cooking could be attributed to the interactions that were formed between amylose–amylose chains and resisted disruption during cooking, thereby partly restricting the accessibility of starch chains to hydrolyzing enzymes. These interactions could be more pronounced with increases in HMT temperature and time, leading to a further decrease in starch digestibility of rice flour.

## Color properties of the rice cake

Color properties of rice cake (*Jeolpyeon*) made with HMT rice flours are shown in Table 3. As expected, *Jeolpyeon* made with white rice flour (J-WR) exhibited the highest lightness ($L^*$) and the lowest redness ($a^*$) and yellowness

**Table 2** Digestibility parameters of native and cooked heat-moisture treated rice flours

| Rice flour | Native flour | | | Cooked flour | | |
|---|---|---|---|---|---|---|
| | RDS (%) | SDS (%) | RS (%) | RDS (%) | SDS (%) | RS (%) |
| F-BR | $45.0 \pm 0.6^{d}$ | $42.5 \pm 2.9^{a}$ | $12.3 \pm 2.5^{b}$ | $88.5 \pm 0.4^{a}$ | $0.8 \pm 0.6^{c}$ | $10.7 \pm 0.5^{c}$ |
| F-HMT1 | $63.1 \pm 1.6^{a}$ | $25.0 \pm 0.5^{d}$ | $11.9 \pm 2.0^{b}$ | $81.7 \pm 0.4^{b}$ | $6.5 \pm 1.6^{b}$ | $11.7 \pm 1.9^{bc}$ |
| F-HMT2 | $55.2 \pm 0.5^{b}$ | $30.0 \pm 2.6^{c}$ | $14.8 \pm 3.1^{ab}$ | $76.6 \pm 0.7^{c}$ | $8.6 \pm 1.5^{ab}$ | $14.8 \pm 2.1^{ab}$ |
| F-HMT3 | $48.3 \pm 2.2^{c}$ | $33.9 \pm 0.4^{b}$ | $17.8 \pm 1.9^{a}$ | $73.2 \pm 2.1^{d}$ | $10.1 \pm 0.2^{a}$ | $16.7 \pm 2.1^{a}$ |

F-BR, brown rice flour; F-HMT1, BR flour heated at 100 °C for 1 h and cooled at 4 °C for 1 h; F-HMT2, BR flour heated at 100 °C for 2 h, cooled at 4 °C for 2 h; F-HMT3, BR flour heated at 110 °C for 2 h, cooled at 4 °C for 2 h

*RDS,* rapidly digestible starch; *SDS,* slowly digestible starch; *RS,* resistant starch

Values followed by the different superscripts in the same column are significantly different ($p < 0.05$)

**Table 3** Color values of rice cakes made with white rice, brown rice, and heat-moisture treated brown rice flours

| *Jeolpyeon* | *L** | *a** | *b** |
|---|---|---|---|
| J-WR | $73.28 \pm 0.31^{a}$ | $-1.71 \pm 0.16^{e}$ | $10.59 \pm 0.39^{e}$ |
| J-BR | $64.31 \pm 0.28^{b}$ | $2.68 \pm 0.10^{d}$ | $21.50 \pm 0.23^{d}$ |
| J-HMT1 | $64.39 \pm 0.32^{b}$ | $4.69 \pm 0.08^{c}$ | $23.52 \pm 0.38^{c}$ |
| J-HMT2 | $56.09 \pm 0.27^{c}$ | $9.32 \pm 0.12^{b}$ | $26.98 \pm 0.40^{b}$ |
| J-HMT3 | $52.80 \pm 0.27^{d}$ | $11.91 \pm 0.07^{a}$ | $29.67 \pm 0.22^{a}$ |

J-WR, *Jeolpyeon* made with white rice flour; J-BR, *Jeolpyeon* made with brown rice flour; J-HMT1, *Jeolpyeon* made with BR flour heated at 100 °C for 1 h and cooled at 4 °C for 1 h; J-HMT2, *Jeolpyeon* made with BR flour heated at 100 °C for 2 h, cooled at 4 °C for 2 h; J-HMT3, *Jeolpyeon* made with BR flour heated at 110 °C for 2 h, cooled at 4 °C for 2 h

Values followed by the different superscripts in the same column are significantly different ($p < 0.05$)

(*b**) values. *Jeolpyeon* made with brown rice flour (J-BR) had a lower *L** value and higher *a** and *b** values as compared to J-WR. Similar results have been reported for cookies and noodles [10, 11]. They suggested that the addition of brown rice flour to cookies and noodles contributed to a darker color due to the natural pigments in brown rice, such as polyphenols and carotenoids. J-BR exhibited a lower *L** value and higher *a** and *b** values compared to its flour counterpart (F-BR, Table 1). These color changes occur during the heating process due to the Maillard reaction between reducing sugars and amino acids. Caramelization and starch dextrinization that occur during heating could also contribute to color changes in the cooked rice.

*Jeolpyeon* made with HMT brown rice flour (J-HMT) showed a decreased *L** value but increased *a** and *b** values. The darkening and browning became more pronounced as the HMT temperature and time increased (Table 3). This tendency was also observed in F-HMT (Table 1). Therefore, the darkening during HMT of flour due to the Maillard reaction directly contributed to the color of rice cakes. Furthermore, color changes among HMT samples were more pronounced in rice cakes than in rice flours. This result could be attributed to the darkening and browning effect that occurs during steaming.

## Textural properties of the rice cake

The main characteristics responsible for consumer acceptance of rice cakes were determined by evaluating the texture and mouth feel. In this study, the texture of rice cake was determined by a two-bite test with a textural analyzer. The textural parameter results of rice cakes after a 6 h storage period are shown in Table 4. Among the tested rice cakes, J-WR exhibited the highest hardness. *Jeolpyeon* made with brown rice flour (J-BR) exhibited lower hardness as compared to that made with white rice flour (J-WR). Reduced hardness of J-BR could be attributed to increased non-starch components including fiber. This non-starch component may lead to the inhibition of structural matrix formation in rice cake during processing. In addition, fiber can act as a water binder, effectively depriving the amylose chains of usable water for recrystallization, resulting in retardation of the hardness increase during storage since the increase in hardness could be mainly due to the rapid aggregation of amylose chains during a short storage time. *Jeolpyeon* made with HMT brown rice flour (J-HMT) exhibited a lower hardness. A further decrease in hardness was found in the rice cake made with rice flour treated at higher temperatures and for longer times (Table 4). This could be associated with rearrangements in the structural network of flour during HMT. Degraded starch chains and other small molecules induced by the applied heat may inhibit starch chain association, resulting in decreased hardness. This decreased hardness could be related to the breakdown and setback among RVA parameters. Reduced breakdown and setback caused by HMT (Table 1) indicates that starches are more stable during continued heating as well as during the shearing and retardation of reassociation of amylose chains

**Table 4** Texture properties of rice cakes made with white rice, brown rice, and heat-moisture treated brown rice flours

| *Jeolpyeon* | Hardness (g) | Adhesiveness (g s) | Springiness | Cohesiveness | Gumminess (g) | Chewiness (g) |
|---|---|---|---|---|---|---|
| J-WR | $4744 \pm 158^{a}$ | $2 \pm 0^{c}$ | $0.47 \pm 0.01^{b}$ | $0.64 \pm 0.03^{a}$ | $3017 \pm 31^{a}$ | $1312 \pm 100^{a}$ |
| J-BR | $3266 \pm 23^{b}$ | $8 \pm 1^{b}$ | $0.57 \pm 0.01^{a}$ | $0.60 \pm 0.02^{b}$ | $2071 \pm 67^{b}$ | $1123 \pm 9^{b}$ |
| J-HMT1 | $2311 \pm 80^{c}$ | $7 \pm 0^{bc}$ | $0.43 \pm 0.00^{c}$ | $0.47 \pm 0.02^{c}$ | $1041 \pm 34^{c}$ | $513 \pm 3^{c}$ |
| J-HMT2 | $1765 \pm 2^{e}$ | $26 \pm 4^{a}$ | $0.35 \pm 0.00^{e}$ | $0.38 \pm 0.01^{e}$ | $634 \pm 2^{e}$ | $230 \pm 11^{d}$ |
| J-HMT3 | $2001 \pm 38^{d}$ | $4 \pm 0^{bc}$ | $0.37 \pm 0.00^{d}$ | $0.44 \pm 0.02^{d}$ | $746 \pm 21^{d}$ | $294 \pm 0^{d}$ |

J-WR, *Jeolpyeon* made with white rice flour; J-BR, *Jeolpyeon* made with brown rice flour; J-HMT1, *Jeolpyeon* made with BR flour heated at 100 °C for 1 h and cooled at 4 °C for 1 h; J-HMT2, *Jeolpyeon* made with BR flour heated at 100 °C for 2 h, cooled at 4 °C for 2 h; J-HMT3, *Jeolpyeon* made with BR flour heated at 110 °C for 2 h, cooled at 4 °C for 2 h

Values followed by the different superscripts in the same column are significantly different ($p < 0.05$)

that occurs during the cooling stage, which accounts for the decreased hardness of J-HMT [20].

Adhesiveness is the property of sticking together of surfaces of different materials. All rice cakes exhibited very low adhesiveness due to their poor sticky property. The rice cake made with HMT rice flour had lower springiness and cohesiveness as compared to J-WR or J-BR. Springiness, which indicates the height ratio between two continuous compressions, refers to the tendency of a compressed sample to recover to its original state. Cohesiveness refers to characterization of the molecular force within a substance upon the applied compression [21]. Reduced springiness and cohesiveness of J-HMT indicates that it possesses a low strength of internal bonds and a weak structure to resist mastication. This may be the result of retarded retrogradation of J-HMT, which could not induce higher elasticity of rice cake. Chewiness and gumminess were also significantly lower in J-HMT as compared to J-WR and J-BR. The chewiness and gumminess were determined by hardness × cohesiveness × springiness and hardness × cohesiveness, respectively. This reduced chewiness and gumminess was thus likely attributable to the low hardness of HMT rice cakes.

## In vitro digestibility of the rice cake

Contents of the rapidly digestible starch (RDS), slowly digestible starch (SDS), and resistant starch (RS) in *Jeolpyeon* are presented in Table 5. The RDS, SDS, and RS contents in J-WR were 65.3, 24.3, and 10.6%, respectively. The RDS, SDS, and RS contents in J-BR were not significantly different from those in J-WR, but J- BR had a marginally lower RDS content and higher SDS and RS contents than J-WR, possibly due to the presence of rice bran in brown rice, which could act as a physical barrier to enzyme attacks. Interestingly, J-BR exhibited a substantially lower RDS content and a higher SDS content as compared to its cooked flour counterpart (cooked F-BR), although the RS content was only marginally different

**Table 5** Digestibility parameters of rice cakes made with white rice, brown rice, and heat-moisture treated brown rice flours

| *Jeolpyeon* | RDS (%) | SDS (%) | RS (%) |
|---|---|---|---|
| J-WR | $65.3 \pm 0.5^{a}$ | $24.1 \pm 3.9^{a}$ | $10.6 \pm 3.5^{d}$ |
| J-BR | $63.6 \pm 4.2^{ab}$ | $23.0 \pm 1.1^{a}$ | $13.4 \pm 2.8^{cd}$ |
| J-HMT1 | $61.0 \pm 0.6^{ab}$ | $22.9 \pm 5.0^{a}$ | $16.1 \pm 3.3^{bc}$ |
| J-HMT2 | $56.3 \pm 3.7^{bc}$ | $27.2 \pm 2.3^{a}$ | $16.5 \pm 0.4^{bc}$ |
| J-HMT3 | $51.1 \pm 3.0^{c}$ | $26.4 \pm 0.9^{a}$ | $22.5 \pm 0.2^{a}$ |

J-WR, *Jeolpyeon* made with white rice flour; J-BR, *Jeolpyeon* made with brown rice flour; J-HMT1, *Jeolpyeon* made with BR flour heated at 100 °C for 1 h and cooled at 4 °C for 1 h; J-HMT2, *Jeolpyeon* made with BR flour heated at 100 °C for 2 h, cooled at 4 °C for 2 h; J-HMT3, *Jeolpyeon* made with BR flour heated at 110 °C for 2 h, cooled at 4 °C for 2 h

*RDS,* rapidly digestible starch; *SDS,* slowly digestible starch; *RS,* resistant starch

Values followed by the different superscripts in the same column are significantly different ($p < 0.05$)

among these two types. These results could be attributed to the differences in physical appearance and preparation process. Cooked F-BR was composed of fine-sized particles, while J-BR consisted of bigger particles with compressed structures resulting from kneading of steamed rice. These compressed structures may act as a physical barrier to enzyme attacks, although the digestion procedure included the mincing step. Furthermore, the preparation of rice cake included a cooling process that may have allowed the rapid retrogradation of amylose chains, resulting in the retardation of enzyme attacks.

HMT of rice cake caused a decrease in RDS content and an increase in RS content, whereas the SDS content was not significantly changed by HMT (Table 5). J-HMT3 had the highest RS levels (22.5%) and the lowest RDS levels (51.1%). As reported by Xu et al. [22], the HMT wheat flour exhibited a high RS content. Chung et al. [3] also observed a significant decrease in RDS content and increase in RS content upon HMT as compared to those of untreated BR. HMT induces the extents of the perfection of

**Table 6** Scores for sensory evaluation of rice cakes with white rice, brown rice, and heat-moisture treated brown rice flour

| *Jeolpyeon* | Color | Flavor | Hardness | Overall acceptability |
|---|---|---|---|---|
| J-WR | $0.3 \pm 0.5^{e}$ | $0.8 \pm 0.5^{e}$ | $4.8 \pm 0.8^{a}$ | $5.9 \pm 0.6^{a}$ |
| J-BR | $2.3 \pm 0.7^{d}$ | $2.4 \pm 0.5^{d}$ | $5.8 \pm 0.9^{a}$ | $5.2 \pm 0.8^{a}$ |
| J-HMT1 | $3.6 \pm 0.5^{c}$ | $3.4 \pm 0.8^{c}$ | $3.3 \pm 0.8^{b}$ | $3.0 \pm 1.0^{b}$ |
| J-HMT2 | $5.5 \pm 0.5^{b}$ | $4.6 \pm 0.5^{b}$ | $3.0 \pm 0.9^{b}$ | $1.6 \pm 0.7^{c}$ |
| J-HMT3 | $6.9 \pm 0.3^{a}$ | $6.7 \pm 0.5^{a}$ | $1.8 \pm 0.8^{c}$ | $1.3 \pm 0.5^{c}$ |

J-WR, *Jeolpyeon* made with white rice flour; J-BR, *Jeolpyeon* made with brown rice flour; J-HMT1, *Jeolpyeon* made with BR flour heated at 100 °C for 1 h and cooled at 4 °C for 1 h; J-HMT2, *Jeolpyeon* made with BR flour heated at 100 °C for 2 h, cooled at 4 °C for 2 h; J-HMT3, *Jeolpyeon* made with BR flour heated at 110 °C for 2 h, cooled at 4 °C for 2 h

Values followed by the different superscripts in the same column are significantly different ($p < 0.05$)

already existing crystalline structures, the retrogradation of amylose chains, and the physical cross-links in amorphous regions. These structural changes may promote rigidity of starch granules and molecules, which thus become less susceptible to digestive enzymes. These results suggest that HMT can be effectively used to control digestibility during the production of rice cake.

### Sensory evaluation of the rice cake

The results of sensory evaluation of rice cake are shown in Table 6. The color score of J-BR and J-HMT was higher than that of W-RJ (Table 6), which exhibited a similar tendency in relation to instrumental color values (Table 3). Particularly, the color score of J-HMT increased as the HMT temperature and time increased. The flavor score of J-BR was slightly higher than that of J-WR and its score became more pronounced as the HMT temperature and time increased (Table 6). The hardness score of J-HMT was much lower than that of J-WR or J-BR. The lowest hardness score was obtained in J-HMT3. There was a strong correlation between the hardness obtained from sensory evaluations and the hardness based on textural properties (Table 4). There was only a marginal difference in the overall acceptability between J-BR and J-WR. However, J-HMT had a lower overall acceptability than J-BR. As the HMT temperature and time increased, overall acceptability scores decreased. This result may be attributed to the off-flavor and dark color generated during HMT.

In conclusion, HMT of brown rice clearly modified the pasting properties, color properties, and in vitro starch digestibility of flour. Rice cake made with HMT brown rice flour exhibited reduced digestibility and retrogradation, but it also showed reduced overall acceptability due to darkening and flavor changes, and these points should be carefully considered while using HMT flour. The rice flour prepared under a proper HMT condition may be applied in rice cake production to control the physical properties and digestibility.

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**Compliance with ethical standards**

**Conflicts of interest** The authors have declared no conflict of interest.

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