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Physicochemical properties of brown rice according to the characteristics of cultivars treated with atmospheric pressure plasma

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ABSTRACT

Plasma technology has been applied to improve shelf life, but research on its effects on the physicochemical properties of brown rice has not been sufficient. In this study, the changes in physicochemical properties of three rice cultivars were investigated after treatment with atmospheric pressure plasma (APP, 0, 10, or 20 min). The water-binding capacity of rice tended to increase with APP treatment, and there was no difference in thermodynamic properties among treatments. Damaged starch content was significantly increased in Dongjinchal and Samkwang cultivars when treated with APP for 20 min. Hardness was decreased by plasma treatment in the Samkwang cultivar and digestibility was increased. Plasma treatment showed different effects on physicochemical properties depending on the brown rice cultivar. The water-binding capacity and hardness affect the texture and food processing suitability of brown rice. Therefore, cultivar and APP treatment conditions should be selected according to the intended purpose of the rice.

1. Introduction

Plasma technology is an emerging non-thermal food processing technique that has attracted the attention of many researchers across the world. Plasma is known for its excellent antimicrobial and surface engineering properties in a range of fields, including the biomedical, textile, and polymer industries (Chizoba Ekezie et al., 2017). Recently, plasma (especially atmospheric pressure plasma, APP) technology has become a powerful and profitable technology for the food industry. APP is highly advantageous for microbial decontamination of food products, including in cases of sporulation and infection by spoilage/pathogenic organisms (Lee et al., 2016). In addition, it has been employed for the processing of packaging materials, to improve barrier properties and promote antimicrobial activity (Puligundla et al., 2017). Other research has reported utilization of APP technology in food processing to improve the functionality of food compounds, enhance seed germination performance, and improve the physicochemical properties of grains (Chizoba Ekezie et al., 2017).

Rice (*Oryza sativa* L.) is a staple food for nearly half of the world's population, and is the third-leading cereal in terms of production. Brown rice, which is hulled directly from rough rice grain, consists of a bran layer (6–7% of its total weight), embryo (2–3%), and endosperm (about 90%) (Chen et al., 1998). It contains more nutritional components, such as proteins, dietary fibers, vitamins, and minerals, than white rice (Lamberts et al., 2007). Brown rice has a good nutritional profile and contains specific phenolic compounds, particularly ferulic acid and diferulates. Additionally, rice bran is a rich source of oryzanols, which have effects on antioxidation and hypocholesterolemia (Wilson et al., 2007). From the viewpoint of health, brown rice should be preferred for consumption because of its higher nutritional value.

However, brown rice is less desirable due to its poor cooking and eating quality. Das et al. (2008) reported that cooked brown rice is dark in appearance, unpalatable, and has hard texture and chewiness properties that are attributed to the tough fibrous bran layer. The presence of the bran layer around the rice kernel also makes it unpalatable. Several methods have been developed to reduce the cooking time of brown rice. These include heat-cool treatment, pre-gelatinization, germination, enzymatic treatment and ultrasonic treatment (Das et al.,

Abbreviations: APP, atmospheric pressure plasma; DBD, dielectric barrier discharge; DSC, differential scanning calorimetry; GOPOD, glucose oxidase-peroxidase

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2008; Afif et al., 1992; Cui et al., 2010; Hirokawa et al., 1986; Ito and Ishikawa, 2004). However, these treatments failed to resolve the disadvantages of low quality appearance, undesirable texture, unpleasant odor and so on (Cui et al., 2010).

Some research has shown that APP can improve the microbial quality, and produce changes in the physicochemical quality of brown rice (Lee et al., 2016; Thirumdas et al., 2016). However, there have been no studies on the effect of APP on the physicochemical characteristics of brown rice cultivars. Therefore, the objective of this study is to evaluate the physicochemical properties of brown rice according to the characteristics of cultivars treated with APP.

2. Material and methods

2.1. Sample preparation and plasma treatments

Brown rice cultivars (Dongjinchal, Samkwang and Palbangmi) were grown in an experimental field of the National Institute of Crop Science located in Suwon, Korea, in 2017. Brown rice was prepared using a rice huller (Model SY88-TH; Ssangyong Ltd., Incheon, Korea). The plasma apparatus used was that of Kim et al. (2015). Briefly, a dielectric barrier discharge (DBD) plasma source was constructed using a rectangular, parallel-piped, plastic container (137 × 104 × 53 mm). The actuator was made of copper electrodes, and a polytetrafluoroethylene sheet was attached to the inner walls of the container. A bipolar square-waveform voltage at 15 kHz was established at one electrode, while the other electrode was grounded. Plasma was generated inside the container with an input power of 250 W. Brown rice was placed in a petri dish at the bottom of the container; it was treated with the APP source for 10 or 20 min.

2.2. Water-binding capacity, swelling power and water solubility

The water-binding capacity of brown rice was measured by mixing 1 g of pulverized sample with 40 mL of distilled water and stirring for 1 h (Kim et al., 2017). The supernatant was removed by centrifugation (Himac CR22N; Koko Holdings Co., Ltd., Tokyo, Japan) at 1500 × *g* for 10 min, and the weight of the precipitated powder was then measured. The water-binding capacity was calculated by subtracting the initial sample weight (g) from the weight (g) of the precipitated sample and expressed as a percentage of the initial sample weight (g). The swelling power and water solubility index were measured by dispersing 1 g of the pulverized sample in 30 mL of distilled water and heating it in a constant temperature water bath at 90 ± 1 °C for 30 min. After centrifugation at 3,000 rpm for 20 min, the supernatant was dried at 105 °C for 12 h and weighed; then, the precipitate was weighed (Woo et al., 2016).

$$\text{Solubility (\%)} = \frac{\text{Dried weight of supernatant (g)}}{\text{Initial sample weight (g)}} \times 100$$

$$\text{Swelling power (\%)} = \frac{\text{Weight after centrifugation (g)}}{\text{Initial sample weight (g)} \times (100 - \text{solubility})} \times 100$$

2.3. Damaged starch content

The level of damage to the starch samples was determined according to the approved AACC (2000) 76-31 method using an assay kit by Megazyme International Ltd. (Bray, Ireland). The measurement and calculation protocols were the same as described by Asmeda et al. (2016).

2.4. Thermal properties

The thermal behaviors of the samples were determined using differential scanning calorimetry (DSC) (Model Q1000 calorimeter; TA Instruments, Inc., New Castle, DE, USA). Each sample was weighed directly in a DSC pan and distilled water was added to obtain a flour-to-water ratio of 1:2.3 (w:w). The pan was then hermetically sealed and allowed to stand for 1 h prior to thermal analysis. Thermal scanning was undertaken from 4 °C to 150 °C at a heating rate of 5 °C/min. The gelatinization onset (T_o), peak (T_p), and conclusion (T_c) temperatures, and the transition enthalpy (ΔH), were determined from the peak area of the DSC endotherm.

2.5. Hardness properties

The hardness of the brown rice was analyzed using testXpert II, a texture analyzer by Zwick Roell (Ulm, Germany). The software used was Texture Expert Exceeds (Texture Technology Corp., Scarsdale, NY, USA). A cylindrical probe sms P/4 was used for measuring the texture. The force was measured in terms of compression (N). The maximum force was 500 N. The instrument was calibrated with a 50 kg load cell. The test speed was 2 mm/s and the probe was allowed to compress 20% of the strain into the sample.

2.6. In vitro digestibility

The *in vitro* digestibility of brown rice after APP was determined according to the method described by Englyst et al. (1992) with modifications. The samples (100 mg) were weighted in screw-capped tubes, and 15 glass beads (4 mm diameter) and 4 mL of sodium acetate buffer (0.5 M, pH 5.2) were added to each tube. The sample tubes were incubated with porcine pancreatic α-amylase (P-7545; Sigma, St. Louis, MO, USA) and amyloglucosidase (A-9913; Sigma) in a shaking water bath (170 rpm) at 37 °C. Aliquots (0.1 mL) were collected at intervals of 0, 10, 20, 60, 120 and 240 min, and mixed with 1 mL of 50% ethanol. After centrifugation (1,500 × *g* for 10 min), the glucose content released into the supernatant from each sample was measured using a glucose oxidase-peroxidase (GOPOD) kit.

2.7. Statistical analysis

The data were analyzed using SPSS software (ver. 18.0; SPSS Inc., Chicago, IL, USA). The statistical analyses used one-way analysis of variance (ANOVA). When significant differences among mean values were detected, Duncan's multiple comparison test was applied at a confidence level of $p < 0.05$.

3. Results and discussion

3.1. Water-binding capacity, swelling power and water solubility

Water-binding capacity and water solubility measured in plasma-exposed brown rice were significantly higher than for the unexposed controls regardless of cultivar. The swelling power of brown rice was increased by APP treatment. Especially, the waxy rice (Dongjinchal) tended to have higher water-binding capacity and water solubility than other cultivars (Table 1). The water-binding capacity indicates the affinity between the sample and water, and is known to increase with the number of amorphous portions in the starch particles, which is related to the swelling index of the starch (Konik-Rose et al., 2001). The water-binding capacity indicates the degree of binding of water penetrating into the amorphous part of the starch particles or adsorbed to the particle surfaces (Wi et al., 2013). The swelling power and water solubility index measure the interactions between amorphous starch chains and the crystalline domains of starch particles and are affected by the proportions of amylose-lipid complexes, amylose and amylopectin (Kim et al., 2012).

The water-binding capacity and swelling power of brown rice tended to increase with APP treatment duration (Table 1). Changes in the microstructure of the rice bran layers caused by the APP allowed

Table 1
Water binding capacity, swelling power, and water solubility of brown rice according to characteristics of cultivars treated with different atmospheric pressure plasma exposed duration.

Cultivars	Time (min)	Water binding capacity (%)	Swelling power (%)	Water solubility (%)
Dongjinchal	0	103.8 ± 1.5[b]	4.2 ± 0.1[a]	7.9 ± 0.4[a]
	10	104.8 ± 1.8[b]	4.3 ± 0.1[a]	8.7 ± 0.3[a]
	20	109.7 ± 2.0[a]	4.3 ± 0.0[a]	8.5 ± 0.9[a]
	SEM[a]	1.47	0.06	0.48
Samkwang	0	99.3 ± 0.0[b]	7.8 ± 0.2[a]	4.9 ± 0.4[a]
	10	100.8 ± 1.2[ab]	7.7 ± 0.1[a]	4.9 ± 0.1[a]
	20	101.5 ± 0.6[a]	7.8 ± 0.1[a]	4.7 ± 0.1[a]
	SEM	0.60	0.12	0.18
Palbangmi	0	85.5 ± 1.7[b]	7.1 ± 0.1[b]	6.2 ± 0.1[b]
	10	92.6 ± 2.1[a]	7.4 ± 0.1[a]	6.9 ± 0.3[a]
	20	92.7 ± 1.1[a]	7.4 ± 0.0[a]	6.4 ± 0.3[b]
	SEM	1.38	0.06	0.19

[a,b]Different letters within same column differ significantly ($p < 0.05$).
[a] Standard errors of the mean (n = 3).

Table 2
Differential scanning calorimetry thermodynamic properties of brown rice according to characteristics of cultivars treated with different atmospheric pressure plasma exposed duration.

Cultivars	Time (min)	To (°C)	Tp (°C)	Tc (°C)	ΔH (J/g)
Dongjinchal	0	57.5 ± 0.6[a]	65.9 ± 0.4[a]	75.1 ± 0.3[a]	5.9 ± 0.2[a]
	10	57.6 ± 0.2[a]	65.9 ± 0.1[a]	75.1 ± 0.3[a]	5.9 ± 0.1[a]
	20	58.0 ± 0.4[a]	66.0 ± 0.1[a]	75.1 ± 0.0[a]	5.9 ± 0.2[a]
	SEM[a]	0.36	0.18	0.18	0.15
Samkwang	0	60.5 ± 0.1[a]	67.0 ± 0.2[a]	74.2 ± 0.5[a]	5.2 ± 0.2[a]
	10	60.7 ± 0.2[a]	67.1 ± 0.2[a]	74.5 ± 0.1[a]	5.4 ± 0.1[a]
	20	60.4 ± 0.2[a]	67.1 ± 0.2[a]	74.7 ± 0.2[a]	4.9 ± 0.1[b]
	SEM	0.16	0.16	0.27	0.10
Palbangmi	0	55.3 ± 0.3[a]	63.7 ± 0.3[a]	73.5 ± 0.6[a]	4.7 ± 0.2[a]
	10	55.9 ± 0.4[a]	63.9 ± 0.3[a]	73.0 ± 0.3[a]	4.9 ± 0.1[a]
	20	56.0 ± 0.4[a]	64.1 ± 0.2[a]	73.5 ± 0.5[a]	4.9 ± 0.2[a]
	SEM	0.30	0.23	0.41	0.15

[a,]bDifferent letters within same column differ significantly ($p < 0.05$).
[a] Standard errors of the mean (n = 3).

water to easily penetrate the brown rice kernel (Chen et al., 2012), which resulted in an increased water-binding capacity during APP. These results starch and protein fragmentation, which could have resulted in a greater number of water-binding sites. There may also have been disruption of the protein matrix around the starch granule that serves as a physical barrier to water absorption (Sarangapani et al., 2015).

3.2. Damaged starch content

Damaged starch content was analyzed according to APP exposure time (Fig. 1). Dongjinchal and Samkwang cultivars showed relatively high levels of starch damage at 20 min of APP treatment, while Palbangmi showed the lowest starch damage with this treatment.

APP treatment increases storage stability due to inactivation of microorganisms, fungi, spores, and viruses (Mai-Prochnow et al., 2014). However, APP damages rice in accordance with energy and exposure time (Niemira, 2012). Damaged starch absorbs more water and thereby changes the food processing properties (León et al., 2006). The mechanism of starch damage induced by APP treatment, and the resistance of Palbangmi starch to damage, require further investigation.

3.3. Thermal properties

The thermal properties of the APP-treated brown rice are shown in Table 2. No significant differences were observed between treatments, except in the Samkwang cultivar.

A high gelatinization temperature is expected to lead to a slower rate of gelatinization of starch, and thus necessitates a prolonged boiling time. Fluctuations in gelatinization temperature also depend on the gas used during plasma treatment. Oxygen is the gas that most effectively damages starch and hydrogen ions can enter starch granules and decompose the starch (Sarangapani et al., 2016). Plasma treatment resulted in an increase in gelatinization temperature and decrease in endothermic enthalpy of gelatinization (Zhang et al., 2014). However, the results showed a different pattern from the water-holding capacity. Thus, additional investigations are required to determine the mechanisms underlying for these results.

3.4. Hardness

Hardness is important for texture evaluation and consumer acceptability (Chen et al., 2012). The hardness measures of brown rice after APP were significantly lower than for untreated brown rice regardless of cultivar (Fig. 2).

Sarangapani et al. reported that cold plasma affected the hardness of parboiled rice, decreasing it according to plasma power and treatment duration (Sarangapani et al., 2015). Plasma treatment can be used effectively to reduce the cooking time required for brown rice (Chen, 2014). Lee et al. indicated that the decrease in hardness due to APP was directly correlated with chewiness, so less work was required to chew

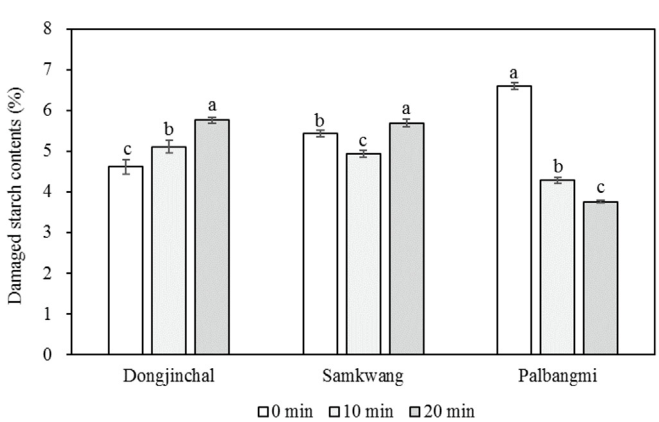

Fig. 1. Damaged starch contents (%) of brown rice according to characteristics of cultivars treated with atmospheric pressure plasma.

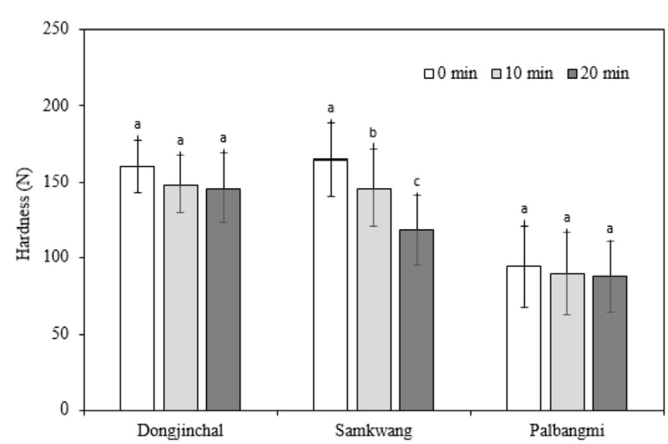

Fig. 2. Hardness (N) of brown rice according to characteristics of cultivars treated with atmospheric pressure plasma.

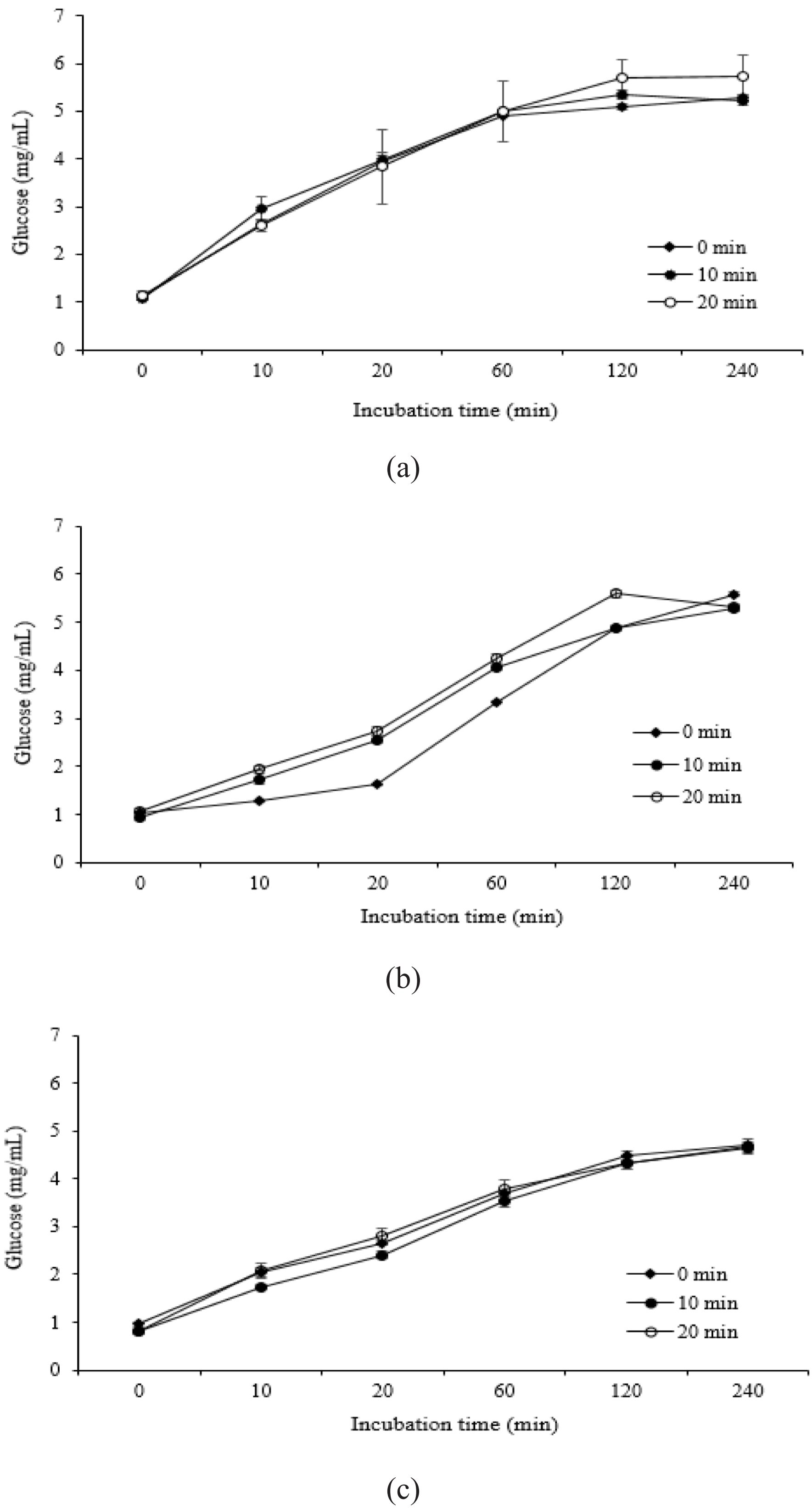

Fig. 3. Glucose content by starch hydrolysis enzyme of brown rice according to characteristics of cultivars treated with atmospheric pressure plasma; (a) Dongjinchal, (b) Samkwang, (c) Palbangmi.

the rice (Lee et al., 2018). Our previous study showed that water absorption rate and α-amylase activity both decreased the hardness of brown rice, which is often seen as a limitation to acceptability despite the higher nutritional quality (Lee et al., 2016).

3.5. *In vitro digestibility*

The digestibility of rice is determined by the starch structure. The digestibility of three rice cultivars after APP treatment was analyzed (Fig. 3). The rate of conversion to monosaccharide glucose was increased by APP treatment duration. There was little difference according to the APP treatment for Dongjinchal or Palbangmi. On the other hand, for Samkwang, digestibility was increased significantly in the 20-min APP-treated group compared to the untreated group from 10 to 120 min.

Starch digestion is caused by amylase in the small intestine or saliva. The digestibility rates depend on the structure of the starch. Generally, digestibility improves with the ratio of amylopectin/amylose (Svihus et al., 2005). Digestibility was negatively associated with hardness. This result was also related to changes in starch structure caused by APP treatment. The increase in digestibility and reduction in hardness caused by APP treatment are expected to increase dietary efficiency.

4. Conclusions

Physicochemical characteristics of three brown rice cultivars were investigated after APP treatment. APP treatment increased water-binding activity and changed the damaged starch content, hardness, and *in vitro* digestibility properties. Applying APP treatment to Dongjinchal resulted in fewer changes in hardness or digestibility; however, it also caused starch granules. The hardness and digestibility of the Samkwang cultivar were significantly affected by APP treatment, which suggests changes in its texture and chewiness. Palbangmi was less susceptible to starch damage by APP treatment, and this deserves further investigation. This study suggests that rice cultivars should be selected according to the intended purpose of the rice after APP treatment. APP treatment enhances shelf life and also affects rice physical properties. It should be possible to develop various applications based on the results of the present study.

Conflicts of interest

The authors declare no conflict of interests.

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