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Property and quality of japonica rice cake prepared with Polygonatum cyrtonema powder

Tian Zheng [a], Huiyun Chen [b], Yuanguo Yu [c], Pan Wang [d], Yongxin Li [a], Gang Chen [a,*], Jinping Si [a,*], Huqing Yang [a,*]

[a] State Key Laboratory of Subtropical Silviculture, Zhejiang A&F University, Hangzhou, 311300, China
[b] Institute of Agricultural Processing Research, Ningbo Academy of Agricultural Sciences, Ningbo, 315040, China
[c] Hemudu Yuanguo Agricultural Products Development Co., Ltd, Yuyiao 315414, China
[d] Pan'an traditional Chinese Medicine Industry Innovation and Development Institute, Zhejiang, 322300, China

A R T I C L E I N F O

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A B S T R A C T

Rice cake is a common traditional food in China. In this study, the effect of Polygonatum cyrtonema (PC) on the qualities and characteristics of rice cake was investigated. The incorporation of PC powder in rice cakes endowed a light-yellow color and increased the water content and water absorption of products. Rheological analysis showed that the rice cake containing PC exhibited weak-gel properties. Additionally, PC (40%) inhibited the rice cake aging and lowered the hardness of rice cakes to 13.86 N after 4 h storage. In vitro starch digestion analysis showed that PC (40%) reduced the digestibility of rice cakes by decreasing the starch hydrolysis rate from 88.70 to 58.95%, displaying a low estimated glycemic index (eGI) of 52.14. The findings mentioned above indicated that the inclusion of PC powder in rice cakes enhanced their characteristics and attributes, which also provided an approach for the development of PC products.

1. Introduction

Rice cake is a traditional seasonal food with several attractive characteristics, including nutritious, smooth, and delicious (Yang et al., 2021). Rice cakes are generally prepared by soaking the japonica rice for several hours, followed by filtering using a water mill, which requires mixing an appropriate amount of water for further steaming and extrusion (Wang et al., 2022). Numerous methods have been adopted to cook rice cakes. These methods include steaming, frying, and stir-frying, with steaming generally being the preferred method. Rice-based products are widely recognized for their easy digestibility and non-allergenicity owing to their gluten-free components (Ferng, Liou, Yeh, & Chen, 2016). However, rice contains a large amount of rapidly digested carbohydrates, which can rapidly increase blood sugar after excessive consumption. Thus, some rice products, including rice cakes, are unsuitable for special populations, e.g., diabetic and obese patients (Wei et al., 2023).

With the rapidly increasing attention on healthy life, the demand for wholesome foods necessitates the improvement of rice products to obtain a variety of new rice cakes. Currently, many rice cakes have been developed to meet the diverse requirements of consumers. Park et al. (2016) incorporated *Codonopsis lanceolata* powder into rice cakes and confirmed their antioxidant activities by assessing the capacity of 1-diphenyl-2-picrylhydrazyl to scavenge free radicals. They also observed that this kind of rice cake exhibited anti-fungal and anti-aging properties. Thus, it is promising to develop a variety of rice cake products with unique characteristics. Park, Liu, Hong, and Chung (2021) reported that adding a given amount of mulberry leaf powder to rice cakes improved the sensory quality and nutrition of Korean rice cakes. Junhee, Malshick, and Saehun (2020) prepared rice cake with a lipophilic bioactive function by adding β-carotene-loaded emulsion powder. Therefore, rice cake products with unique features can be developed by properly incorporating bioactive food materials into rice flour.

Polygonatum cyrtonema (PC) is considered a food resource by the ancient Chinese. PC is an important medicine food homology herbal substance recorded in China Pharmacopoeia (2020 edition) (Si & Zhu, 2021; Xia et al., 2021). Polygonatum is divided into three basal species, Polygonatum sibiricum, P. kingianum, and P. cyrtonema, according to the shape of the rhizomes, which are brownish-yellow in color on the surface and yellowish-white in color on the cross-section (Shi et al.,

* Corresponding authors.
E-mail addresses: chenggangdeng@126.com (G. Chen), lssjp@163.com (J. Si), yanghuqing@sohu.com (H. Yang).

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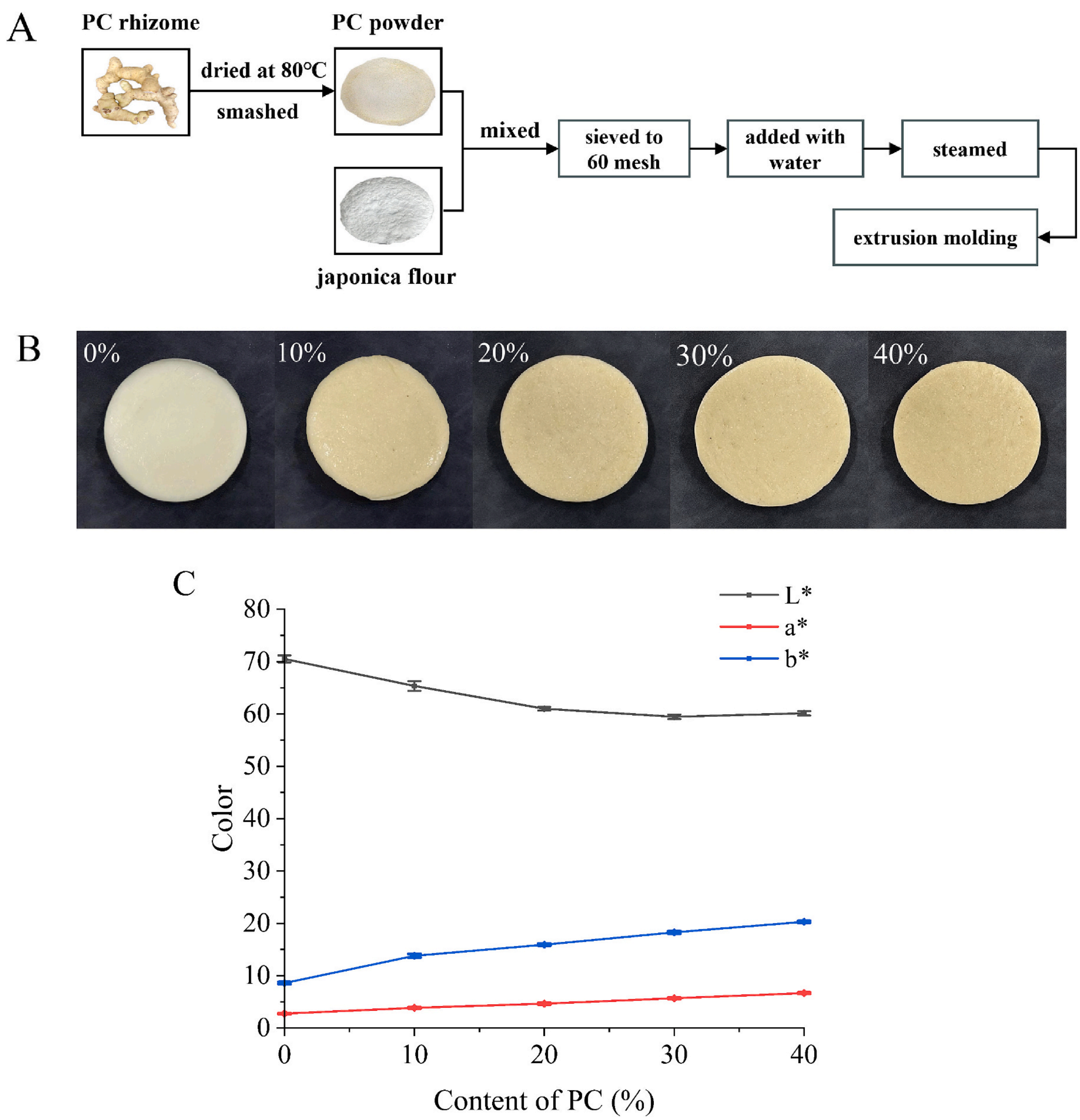

Fig. 1. (A) The preparation of PC rice cakes. (B) The appearance of rice cakes varies with the content of PC powder. (C) change in the surface color parameters L*, a*, and b* of rice cakes in the presence of PC.

2023). Previous studies on PC uncovered a series of components, such as different types of flavonoids, saponins, polysaccharides, alkaloids, and essential amino acids (Gan, Chen, Shi, & Zhou, 2013). Similar to Jerusalem artichoke, the rhizome of PC contains many non-starch polysaccharides and oligofructose, which are globally considered high-quality dietary fiber (Si & Zhu, 2021). The fructan and galactan from PC have been proven to exhibit significant prebiotic activity for stimulating the growth of bifidobacteria and lactobacilli (Zhang, Chen, & Luo, 2021). Studies have also demonstrated the other potential bioactive functions of PC, such as regulating blood sugar (Li et al., 2020), antioxidative activity (Li, Chen, Liu, Xu, & Zhang, 2021), anti-fatigue (Shen et al., 2021), and antibacterial activity (Li, Thakur, Liao, Zhang, & Wei, 2018; Li, Wang, Chen, Yu, & Feng, 2018).

Currently, PC is considered one of the important raw materials in developing the homology of medicine and food. Raw PC contains n-hexanal, camphene and other stimulating ingredients, numbness in the mouth and tongue when taking, usually not directly consumed (Liao, Ye, & Zhou, 2021). The traditional practice of PC is nine steams and nine preparations, but it is too sweet and prone to burnt bitterness and is darker in color, so it is usually used as a medicinal herb (Liao et al., 2021). During the drying and steaming process, PC reduces the astringency and numbness, and can be used in food processing (Wang, Wang, Zhu, & Wang, 2014). Moreover, the color of PC is moderate and can be added to food to give a healthy color, which is favored by some consumers who are keen on health and wellness. For example, Wang et al. (2023) developed a new variety of wolfberry wine that contained PC flavonoids, which exhibited potent antioxidant properties. Thus, this method offers a strategy for the development of flavonoid fermentation. In our previous research, adding PC to baked cookies improved the appearance and edible quality of cookies because PC itself was light yellow and participated in the intense Maillard reaction during baking, resulting in a more attractive golden color than the control group (Xiong et al., 2023). In addition, the PC endowed the prepared cookie products with the low glycemic index feature. At present, the influence of PC on the property of rice cakes has not been reported. In this study, the traditional japonica rice cake was selected as the model rice cake, which is especially popular in the Asia southern part of China (Yang et al., 2021). The quality, texture, rheological, and digestibility characteristics of rice cakes prepared with PC were studied in this work. The slowly digestive rice cake was obtained with an anti-aging property. Therefore, it is promising to enhance the nutritional and commercial value of rice cakes to a certain extent, expanding the development of PC food. This study also provides an approach for improving rice cake products.

2. Materials and methods

2.1. Materials

Japonica rice flour was supplied by Wuhu Shennong Food Co., Ltd. (Wuhu, China; protein 8.5%, fat 1.1%, carbohydrate 78.1%). PC was supplied by Yipuyuan HuangJing Technology Co., Ltd. (Xinhua, China). Porcine pancreatic α-amylase (A3176-500KU, 11 U/mg) was purchased from Sigma-Aldrich Co. Ltd. (MO, USA). Pepsin (P816235-100 g, 3000 U/mg) and amyloglucosidase (A800618–50 mL, 100,000 U/mL) were obtained from Shanghai Maclin Biochemical Technology Co., Ltd. (Shanghai, China). All the other chemicals were of analytical grade and provided by Xilong Chemical Co., Ltd. (Guangdong, China).

2.2. Preparation of rice cakes

The preparation of PC rice cakes is shown in Fig. 1A. The PC rhizome was dried first and then crushed to 60 mesh powder using a grinder DJ-40 (Shanghai Dianjiu Traditional Chinese Medicine Machinery Manufacturing Co., Ltd., Shanghai, China). The mixture of PC powder and japonica rice flour was evenly mixed at different proportions (0, 10, 20, 30, and 40%, *w*/w). Then, distilled water was added to the mixture at a 45%(*w*/w) ratio. The prepared mixture was steamed for 15 min and immediately placed in a rice cake machine for extrusion molding at high temperature. The rice cakes for each formulation were prepared thrice, with five samples per batch for subsequent measurements (Park et al., 2021).

2.3. Determination of rice cake moisture

Moisture contents of rice cake were determined using the AOAC Official Method (AOAC, 2000). The specimen was dried in an oven set at 105 °C for 4 h until a constant weight was achieved. The computation of the moisture content of the specimen was based on the percentage ratio between the weight loss and the initial weight of each specimen.

2.4. Measurement of water absorption and cooking loss

Water absorption and cooking loss of rice cakes were determined according to the methodology described by Yang et al. (2021). A sample of (30 g) of rice cake was initially boiled in 300 mL of distilled water for 10 min. Subsequently, the rice cake was taken out, and the water that was left over was collected with a beaker. Gravimetric analysis was used to determine the solid weight in the water after it was dried to a constant weight at 105 °C in a hot air oven. Eqs. (1) and (2) were used to calculate the water absorption and cooking loss of rice cakes.

$$\text{Water absorption } (\%) = \frac{\text{weight of (cooked rice cake} - \text{fresh rice cake)}}{\text{weight of fresh rice cake}} \times 100 \quad (1)$$

$$\text{Cooking loss } (\%) = \frac{\text{remaining solid content after drying}}{\text{weight of fresh rice cake}} \times 100 \quad (2)$$

2.5. Color measurement

The color of the exterior of rice cakes was measured using a Chroma Meter (CR-400, Kinolta Minolta, Warrington, UK). Each test was performed five times. Parameter L* represents the lightness of color. Parameter a* represents a red–green color. The positive and negative a* values indicate redness and greenness, respectively. Parameter b* represents the yellow–blue color. The positive and negative b* values represent yellowness and blueness, respectively (Wang et al., 2022).

2.6. Texture analysis

The texture of the rice cake was examined using a TA.XT plus texture analyzer from Stable Micro Systems based in Godalming, UK. The freshly prepared rice cakes and cooked rice cakes were measured separately. Test conditions were as follows: test mode of TPA, pre-test rate of 2.0 mm/s, in-test rate of 1.0 mm/s, post-test rate of 1.0 mm/s, compression ratio of 60%, interval time of 2 s between compressions, and induction force of 5.0 g. Parameters for hardness, adhesiveness, cohesiveness, springiness, and gumminess were determined. Each sample was tested at least 5 times, and the results were averaged. To study the aging of rice cakes, the hardness of rice cakes was selected as a crucial indicator and determined with time during the storage of rice cakes.

2.7. SEM

All of the rice cakes were crafted following the procedure described in section 2.2 and cut into evenly sized thin pieces. After 2 h of equilibration at ambient temperature, all the rice cakes were stored in a − 80 °C fridge and quickly frozen for 4 h. Afterward, the frozen rice cakes were transferred to a freezing dryer for lyophilization (Hou, Zhao, Yin, & Nie, 2023). The microstructure of lyophilized rice cake samples was measured using a SEM (TM4000Plus, Hitachi Co., Ltd. Japan). Morphological images of each sample were obtained at 15.0 kV acceleration voltage.

2.8. Dynamic rheological property determination

The dynamic rheological properties of rice cakes were determined using a rotational rheometer (DHR-1, TA Company, USA). The prepared rice cakes were placed on the central platform of the rotational rheometer and then covered with a plate. The dynamic rheological properties of all rice cakes were investigated using frequency dynamic scanning tests with a plate probe diameter of 35 mm. The measurement spacing was 1 mm at 25 °C. The frequency range for the scanning test was 0.1–10 Hz.

2.9. In vitro starch digestion

The in vitro starch digestion analysis was performed using the method described by Goñi, Garcia-Alonso, and Saura-Calixto (1997), with some modifications. The rice cake (0.8 g) was ground, mixed with 30 mL distilled water, and stirred at 150 r/min for 10 min at 37 °C before the digestion stage. To simulate gastric digestion, 0.8 mL of 1 M hydrochloric acid and 1 mL of pepsin solution were added into a conical flask and stirred at 150 rpm for 30 min at 37 °C. To stop gastric digestion, 2 mL of 1 M $NaHCO_3$ solution was added to the flask. A 5 mL 0.1 M sodium acetate buffer (pH = 6.0) was added to the solution for small intestinal digestion to keep the constant pH. Furthermore, 50 μL of amyloglucosidase solution and 3 mL of porcine pancreas α-amylase solution prepared with 0.1 M of sodium acetate buffer (pH = 6.0) were added to the hydrolysate immediately. The 50 mL modified solution was hydrolyzed for 180 min at 37 °C under 200 rpm. Precisely, 0.8 mL of hydrolysate was extracted every 30 min. Subsequently, 3.2 mL of anhydrous ethanol was introduced into the solution and centrifuged at 10,000 rpm for 10 min (Xiong et al., 2023). The glucose concentration in the incubated mixture with dinitrosalicylic acid was measured using an ultraviolet spectrophotometer (757 N, INESA, China). The absorbance value was measured at 540 nm. The starch digestibility rate (%) was

Table 1
Effect of PC on the moisture and water absorption and cooking loss of rice cakes.

Content of PC (%)	Moisture content (%)	Water absorption (%)	Cooking loss (%)
Control	39.53 ± 0.62b	106.02 ± 0.63c	1.65 ± 0.33d
10	41.13 ± 0.44a	108.25 ± 0.56ab	2.38 ± 0.40c
20	41.89 ± 0.57a	109.16 ± 0.44a	3.83 ± 0.12b
30	41.46 ± 0.64a	107.64 ± 0.49b	6.23 ± 0.28a
40	41.26 ± 0.62a	106.20 ± 0.15c	6.79 ± 0.17a

Values in the same column with different letters are significantly different ($P < 0.05$).

calculated using Eq. (3). Origin 9.0 was used to plot the starch digestibility versus the time curve for each group of rice cakes.

$$\text{Starch digestibility rate (\%)} = \frac{\text{Content of hydrolyzed glucose} \times 0.9}{\text{Total starch weight}} \times 100\% \tag{3}$$

Based on the starch digestion rate expressed in Eq. (3), three starch nutrient fractions were identified for each group of rice cake: rapidly digestible starch (RDS, digested within 30 min), slowly digestible starch (SDS, digested between 30 min and 120 min), and resistant starch (RS, undigested after 180 min). The hydrolysis index (HI) and expected glycemic index (eGI) were calculated following the method of Goñi et al. (1997). The HI and eGI were calculated using Eqs. (4) and (5), respectively. HI and AUC were on behalf of the hydrolysis index and the area below the hydrolysis curve (0–180 min), respectively.

$$HI = \frac{AUC}{\text{AUC white bread}} \tag{4}$$

$$eGI = 0.862HI + 8.1981 \tag{5}$$

2.10. Sensory characteristics

The sensory characteristics were estimated using our previously described method (Xiong et al., 2023). A semi-trained 10 female and 10 male panelists (ages ranging from 20 to 30) participated in the descriptive examination of the rice cake samples. Samples with a dimension of 2 cm × 2 cm 2 cm were placed on white plates and randomly assigned three-digit codes. To cleanse their palates in between samples, the panelists were instructed to rinse their mouths with water. Each sample was evaluated using a 25-point hedonic scale for color, appearance, aroma, and taste as part of the descriptive analysis process. The final scores are calculated together as the overall acceptance score.

2.11. Statistical analysis

Every experiment was performed at least three times, and the mean ± standard deviation was used to describe the findings. The data in this study were analyzed for significance using one-way analysis of variance with SPSS 26.0, with $P < 0.05$ being a significant difference. The images were drawn using Origin 2022 (Stat-Ease Inc., Minneapolis, MN, USA).

3. Results and discussion

3.1. Moisture, water absorption, and cooking loss of rice cakes

Moisture content strongly correlated with the sensory and quality of rice cakes. As shown in Table 1, the water content of the control sample was approximately 39.53%. The addition of PC powder slightly affected the water content, water absorption, and cooking loss of rice cakes ($P < 0.05$). As the PC content increased, the water content and water absorption initially increased and then decreased, achieving the highest values of 41.89% and 109.16%, respectively, at 20% of PC. This phenomenon may be attributed to the polysaccharides and oligosaccharides

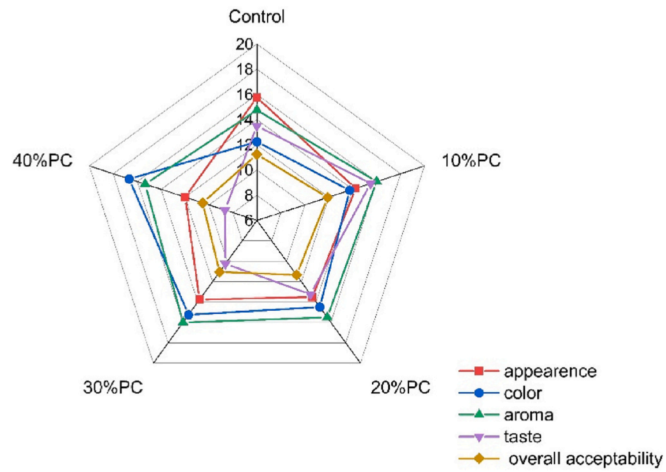

Fig. 2. Effect of PC on the sensory quality of rice cakes. The scores in the figure are shown with mean values.

rich in PC (Si & Zhu, 2021), which have a great capacity to bind water molecules in rice cakes and other food matrixes (Park et al., 2021). The effect of PC on moisture content and water absorption of rice cakes was similar to that of inulin. The water absorption of rice cakes initially increased and then reduced as the inulin concentration increased. (Yang et al., 2021).

In contrast to variations in moisture content and water absorption of rice cake, the cooking loss of rice cake increased as PC powder content increased compared with the control sample. The cooking loss was below 5% as the PC powder content was below 30% (Table 1). In particular, the cooking loss of all rice cakes remained below 7%, even at the PC content of 40%. The variation in cooking loss in this study was comparable to that of rice cakes made with inulin (Yang et al., 2021). This phenomenon might be attributed to the embedding of a significant number of PC particles within the gel network structure of rice cakes, which reconstructed the microstructure of rice cakes, causing incomplete gelatinization. As a result, some PC granules and starch granules fell off from the network structure during cooking (Yang et al., 2021).

3.2. Color of rice cakes

The appearance of rice cakes is shown in Fig. 1B, and the color difference of rice cakes is shown in Fig. 1C. The color of rice cakes gradually changed from white to light yellow as the PC powder content gradually increased. This change in color is attributable to the flavonoids or other pigmentation substances of PC (Zhao et al., 2018). As shown in Fig. 1C, significant differences were observed between the control and the rice cakes containing PC in the surface color parameters L*, a*, and b*. As PC powder content increased, the L* value of the rice cake decreased compared with the control. Particularly, the L* of rice cakes containing 30% PC decreased from the initial value of 70.52 to 59.46. In contrast, the a* and b* values increased as PC powder content increased. The result showed that the incorporation of PC weakened the brightness of rice cakes, enhancing their green and yellow values. Free amino groups in proteins and reducing sugars triggered the Maillard reaction under mild and heating conditions, contributing to the emergence of yellow color (Zhang et al., 2019). Therefore, the yellow–green color of rice cake can also be attributed to the addition of PC powder containing a variety of reducing sugars and free proteins (Oh, Choi, Choi, & Baik, 2020).

3.3. Sensory evaluation of rice cakes

A sensory evaluation was conducted to estimate the quality of rice cakes. As shown in Fig. 2, the control achieved the highest score in the

Table 2
Effect of PC on the textural properties of rice cakes.

Content of PC (%)	Hardness (N)	Adhesiveness(N.*sec*)	Cohesiveness	Springiness	Gumminess (N)
Control	17.31 ± 0.15a	26.13 ± 2.19a	0.49 ± 0.15b	8.46 ± 0.15a	9.49 ± 0.96a
10	10.30 ± 0.57bc	6.10 ± 0.10b	0.54 ± 0.03b	8.99 ± 0.23a	5.54 ± 0.46b
20	8.51 ± 0.90c	4.82 ± 0.95bc	0.52 ± 0.01b	6.86 ± 0.58b	4.20 ± 0.67b
30	12.79 ± 1.12b	0.73 ± 0.09d	0.67 ± 0.02a	2.27 ± 0.21d	5.01 ± 0.13b
40	12.41 ± 0.46b	1.87 ± 0.41 cd	0.42 ± 0.01c	5.21 ± 0.20c	5.18 ± 0.23b

Values in the same column with different letters are significantly different ($P < 0.05$).

sample appearance. In the color category, the sensory score of samples containing 40% PC was higher than that of other groups with a unique light-yellow color. The color of PC rice cake could reflect the health of traditional Chinese medicine food and was highly favored by consumers who were passionate about healthy food (Liao et al., 2021). Therefore, an appropriate PC can improve the sensory quality of the product as an auxiliary ingredient. The rice cake prepared with PC had a unique flavor similar to that of PC, while the control group only had the rice flavor of japonica rice. However, the poor taste of the rice cake containing 30% or 40% PC content was attributed to the intrinsic taste of the bitter and astringent flavors of PC and the poor adhesiveness and springiness. Thus, the sensory scores of samples containing 30% and 40% PC were much lower than those of other groups in the taste evaluation. It was shown that the sensory quality of rice cakes was affected only when the PC concentration was too high. In terms of overall acceptance, the sensory scores of samples containing 10% and 20% of PC display a higher acceptance. Studies have confirmed that the addition of PC powder enhanced food quality (Li et al., 2023). For instance, the addition of PC powder to bake cookies resulted in a smoother surface and more attractive color (Xiong et al., 2023). In the study, the addition of PC improved the quality of rice cakes and endowed them with a low-GI characteristic.

3.4. Textural property of rice cakes

As shown in Table 2, the hardness, adhesiveness, cohesiveness, springiness, and gumminess varied with the content of PC in rice cakes ($P < 0.05$). The incorporation of 20% PC powder decreased the hardness of rice cakes to a minimum value of 8.51 N. Similarly, the adhesiveness of rice cake containing PC significantly decreased from 6.10 to 0.73 N·*sec*, which was much lower than the value of control (26.13 N·sec). For example, the adhesions of rice cakes containing 10% and 20% of PC were 6.1 and 4.82 N·sec, respectively. In this study, the effects of PC on the springiness and gumminess of rice cakes were similar to that on the hardness of rice cakes. The springiness and gumminess of rice cakes were largely reduced in the presence of PC. The change of adhesion of rice cake was related to the amount of PC added. Table 2 showed that the addition of 30% of PC significantly improved cohesion to 0.67 compared to 0.49 in the control group.

PC and starch were heated under high temperature in the presence of water, and then cooled down, and amylose was entangled and ordered to transform amorphous starch paste into gel (Dang, Imaizumi, Nishizu, Anandalakshmi, & Katsuno, 2023). Amylose leaching from starch after gelatinization enables the creation of a gel network in the form of a double helix in the process of cooling (Chen, Guo, & Zhu, 2023). Rice glutenin forms aggregates during the pasting process and adheres to the starch gel network structure through hydrophobic interactions and hydrogen bonding with glutinous rice starch (Li, Thakur, et al., 2018; Li, Wang, et al., 2018). Overall, the low starch and protein content of PC itself and the high water absorption of polysaccharides may have damaged the integrity of the three-dimensional network structure of the starch gel and affected the texture of the rice cakes (Li, Thakur, et al., 2018; Li, Wang, et al., 2018). The hardness of rice cakes depends on the content of straight-chain starch. A study has confirmed that the hardness of rice cakes decreased with the decreasing straight-chain starch content (Park et al., 2021). The addition of PC powder to rice cakes may form a complex between amylose and PC, retarding amylose chain entanglement and reducing the hardness. As the amount of PC added increases, the hardness of rice cake decreased while its cohesion increased. The adhesive strength is related to both of them, which is in line with the characteristics of semi-solid food. The polysaccharides in PC are negatively charged (Shi et al., 2023). The interaction between polysaccharides and proteins is mainly electrostatic between the anionic groups of polysaccharides and the positively charged groups of proteins (Huang, Mao, Li, & Yang, 2021; Jamilah et al., 2009). The addition of PC reduced the protein content in the mixtures, which might weaken the electrostatic attraction between rice protein and polysaccharides, indirectly altering hydrogen bonding and hydrophobic interactions, resulting in a decrease in hardness with the addition of PC (Li, Thakur, et al., 2018; Li, Wang, et al., 2018). Adhesion is the capacity of a material to adhere to itself. Adhesiveness is defined as the property of attraction or adhesion between the molecules of different substances at their surfaces (Kim et al., 2012). Therefore, observations on rice cake texture are primarily attributed to the changes in starch properties (Chen et al., 2023). During the preparation of rice cakes, the hydrated straight-chain starch and branched-chain starch were released in the starch gelatinization process (Dang et al., 2023). The inhomogeneity of japonica rice flour and PC in the rice cakes resulted in a loose structure and weak gumminess of rice cakes. Thus, the rice cake viscosity decreased in the presence of PC.

The addition of PC also altered the texture characteristics of rice cakes after cooking ($P < 0.05$) (cf. supplementary information). The hardness and gumminess of rice cakes significantly decreased in the presence of PC. For example, the hardness decreased from 7.02 to 3.06 N as the PC content increased from 0 to 40%. The adhesiveness of rice cakes gradually increased from 2.48 to 3.76 N.*sec* as the PC content increased from 0 to 20%. In terms of the cohesiveness, there is no significant difference among all rice cakes. The addition of PC changed the composition of protein, fat, and dietary fiber in rice cakes, which may also contribute to the change in product texture (Kim et al., 2012).

3.5. Change of rice cakes texture during storage

The aging of starch inverts the gelatinized starch, resulting in the aggregation and rearrangement of starch molecules, which is associated with an increase in the hardness of starch-based foodstuffs (Dang et al., 2023). Hardness is a typical indicator that reflects starch retrogradation and is used to study the staling characteristics of rice cakes. As shown in Fig. 3A, the hardness of the control group rapidly increased from 6.22 to 59.81 N after storage for 4 h. In contrast, the hardness of rice cakes containing 30% and 40% of PC increased slowly. For example, the hardness of the rice cake containing 40% PC increased from 3.90 N to 13.86 N. The hardening of rice cakes during storage was mainly attributed to water loss, starch retrogradation, and water redistribution (Matignon & Tecante, 2017). During the storage of rice cakes, starch molecules are rearranged after the rapid cooling of rice cakes, facilitating the rapid entangling of amylose chains, which reduces the hydration and increases their hardness (Chrastil & Zarins, 1992). The observation in our study may result from the decrease in the amylose contents of rice cakes by adding PC, which finally inhibits the aging of

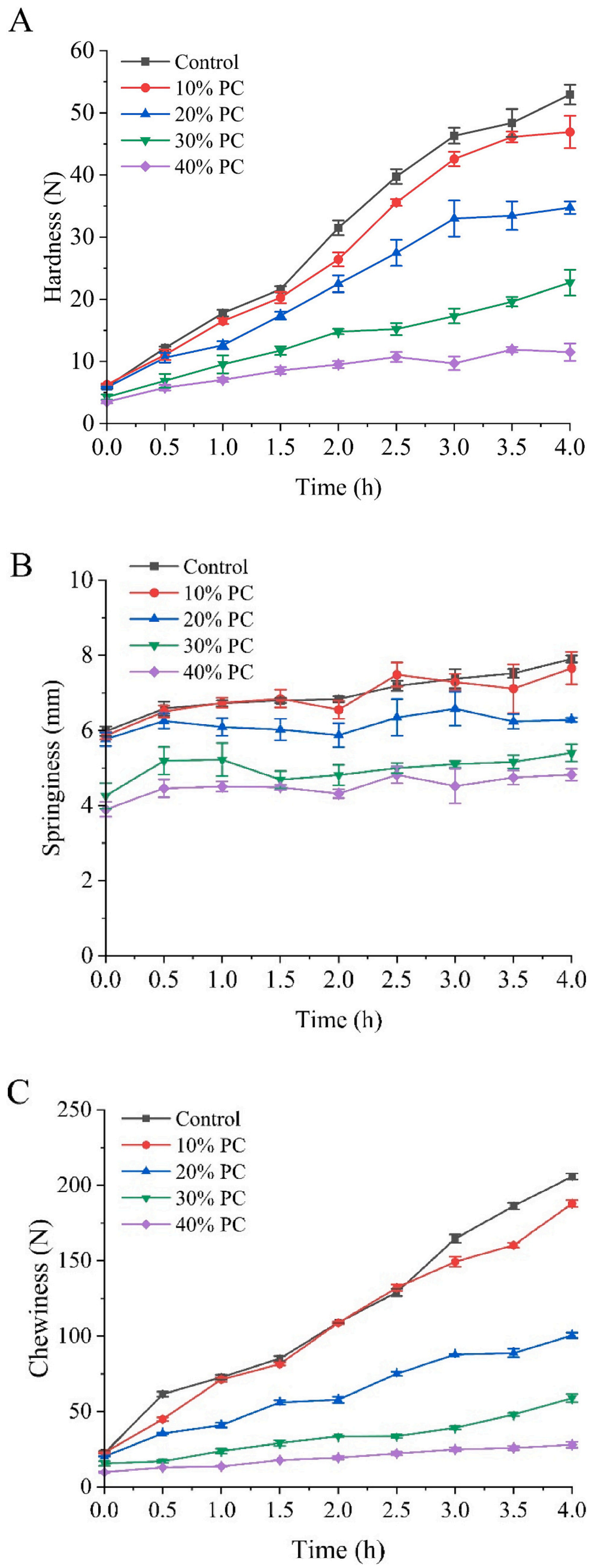

Fig. 3. Influence of PC on the hardness (A), springiness (B), and chewiness (C) of rice cakes during 4 h storage at 4 °C.

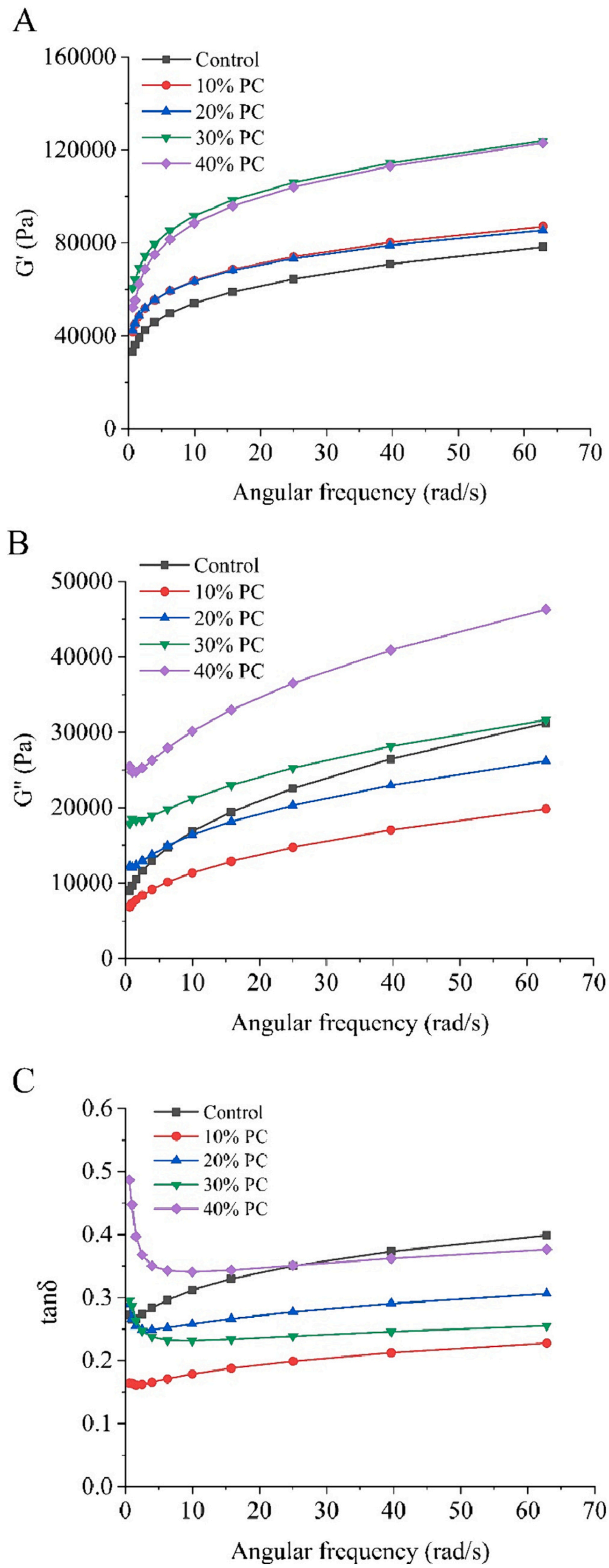

Fig. 4. Frequency sweep data of dough with different amounts of PC. (A) The elastic modulus G′ versus frequency. (B) The viscous modulus G″ versus frequency. (C) The loss tangent tan versus frequency.

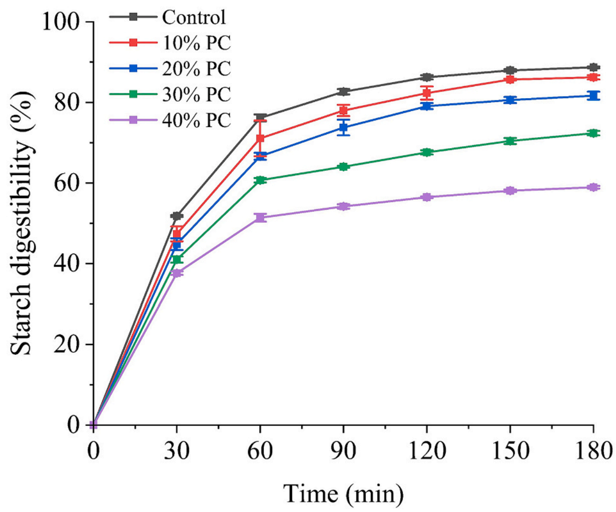

Fig. 5. Effects of PC on starch digestibility of rice cakes.

starchy foods (Ferng et al., 2016).

Fig. 3A also shows that the hardness of rice cake is inversely correlated to the contents of PC. On the one hand, it may be that PC polysaccharides adsorbed on the surface of starch, hindering the aggregation and rearrangement of linear starch, and reducing the water absorption and swelling properties of starch; On the other hand, polysaccharide might affect the gel network through non covalent interaction with rice protein, delaying the movement of water and the recrystallization of starch (Kotsiou, Sacharidis, Matsakidou, Biliaderis, & Lazaridou, 2022). The increase in PC content in rice cakes significantly increased their water-holding capacity, which prevented them from drying out. Similar results were observed when rice cakes were made with *Bombay Robinia pseudoacacia* powder (Indriani, Bin Ab Karim, Nalinanon, & Karnjanapratum, 2020). Indriani and coauthors assumed that the powder of *Bombay Robinia pseudoacacia* contained proteins and fibers, which affected the network of gelatinized starch and weakened the structural skeleton of the rice cake.In this study, our results showed that adding PC powder inhibited the staling speed of rice cakes. As shown in **Fig. 3B** and **C**, the increase in springiness and chewiness caused by the addition of PC inhibited the staling process for 4 h, which is in line with the trend of rice cake staling, indicating that the addition of PC not only inhibits the staling of rice cake but also maintain the texture of rice cake to some extent.

3.6. Rheological properties of rice cakes

The influence of PC powder on the rheological behavior of rice cakes was investigated by determining the viscoelasticity. G′ describes the energy stored in the sample as well as recovered from it during each cycle of sinusoidal deformation, reflecting its solid characteristics (Tsatsaragkou, Papantoniou, & Mandala, 2015). G″ is a measure of the lost or dissipated energy during each cycle to indicate the liquid property (Das & Bhattacharya, 2019). As shown in Fig. 4, the curves of G' and G" of rice cakes plotted by dynamic oscillation test data varied with the contents of PC.

As shown in Fig. 4A, the elastic modulus G' is greater than the viscous modulus G" in all frequency ranges, indicating that the rice cake has a weak-gel characteristic. Consistent with the observation above, the values of loss tangent (tanδ = G"/G') for all samples were <1. Compared with the control, the addition of 30% or 40% of PC significantly increased the G' value of rice cakes. In addition, G' and G" achieved the highest value at 30% and 40% of PC, respectively. G' and G" also increased with the increase in frequency, suggesting that the viscoelasticity of rice cakes increased. Rice cake is a unique colloid in which polymer molecules or colloidal particles create a network structure between the solid phase and the liquid phase (Wang et al., 2022). The addition of PC changed the content and proportion of starch in the system and strengthened the interaction between polysaccharides and starch, thereby increasing the G' and G" of rice cakes (Lu, Brennan, Serventi, & Brennan, 2018).The changes in G' and G" may also be due to the hydrophilic effect of PC polysaccharides and the promotion of protein denaturation during heating, exposing hydrophobic groups in the undeveloped protein structure, which exacerbate the molecular entanglement between the polysaccharides and rice proteins through covalent and non-covalent bonding interactions (Huang et al., 2021; Li, Thakur, et al., 2018; Li, Wang, et al., 2018).

3.7. In vitro starch digestibility of rice cakes

During the gelatinization of starch, it undergoes an order-to-disorder phase transition, which can irreversibly break its semi-crystalline structures and alter the nutritional properties of starch-based foods (Li, 2022). As shown in Fig. 5**,** the starch hydrolysis rate rapidly rose in each group within the first half-hour. The addition of PC into rice cakes significantly interfered with the digestion rate of rice cakes in a concentration-dependent manner. In the control, the concentration of the reducing sugar was 370.19 mg/g after complete intestinal digestion within 90 min. Compared with the control, the concentration of reducing sugar was markedly decreased in the presence of PC. In addition, the order of starch hydrolysis degree after the digestion for 180 min was as follows: Control (88.70%) > 10% of PC (86.21%) > 20% of PC (81.67%) > 30% of PC (72.37%) > 40% of PC (58.95%). The results showed that PC had an inhibitory effect on the digestion rate of rice cakes, which is consistent with our previous results on baked cookies (Xiong et al., 2023). The digestibility of starch is one of the important indicators for estimating starchy foods, including rice, which directly correlates with the change in blood sugar levels in the human body after ingestion (Goñi et al., 1997). We determined the in vitro starch digestibility and evaluated the eGI and starch content of rice cakes (cf. supplementary information). Generally, starches can be classified as RDS, slowly digestible starch (SDS), and resistant starch (RS) based on their digestibility (Englyst, Kingman, & Cummings, 1992). The contents of RDS, SDS, and RS in the control were 51.81, 34.40, and 13.79%, respectively. The RS of the rice cake containing 40% PC increased to 43.53%. In addition, the RDS of the cake reduced to 37.64%, which was much lower than that of the control. The eGI value of the rice cake containing 40% PC decreased to 52.14, much lower than the eGI value (73.85) of the control.

PC contains polysaccharides, flavones, and other components (Tamura, Singh, Kaur, & Ogawa, 2018). It was assumed that PC wrapped the starch particles by forming a protective layer, which might reduce the contact area with α-amylase (Cai, Shen, Li, Xiong, & Li, 2023). Unlike starch, PC's own polysaccharides were not digested and do not generate blood sugar (Shi et al., 2023). And the study found that flavonoids could inhibit α-amylase activity, with anti hyperglycemic effects (D'Costa & Bordenave, 2021). Therefore, the proteins and polysaccharides in PC might form RS in rice cakes by binding to starch particles, as well as through secondary forces, hydrogen bonds, electrostatic interactions, etc., thereby reducing the digestibility of starch (Xiong et al., 2023). In addition, the components of PC, such as flavonoids and saponins, showed the capacity to inhibit amylase (Shi et al., 2023). Since PC polysaccharides are not fully digested and absorbed during digestion, they are mainly converted into short-chain fatty acids by *bifidobacteria* at the end of the intestine, which may promote insulin secretion and regulate blood glucose (Shi et al., 2023). Therefore, the addition of PC to the rice cakes decreased the starch hydrolysis rate by inhibiting amylase activity, thus modifying the starch gel structure and degree of gelatinization or acting as a physical barrier (Papoutsis et al., 2021).Dietary flavonoids in PC may enter the circulatory system through the intestinal tract and work with the intestinal microbiota to

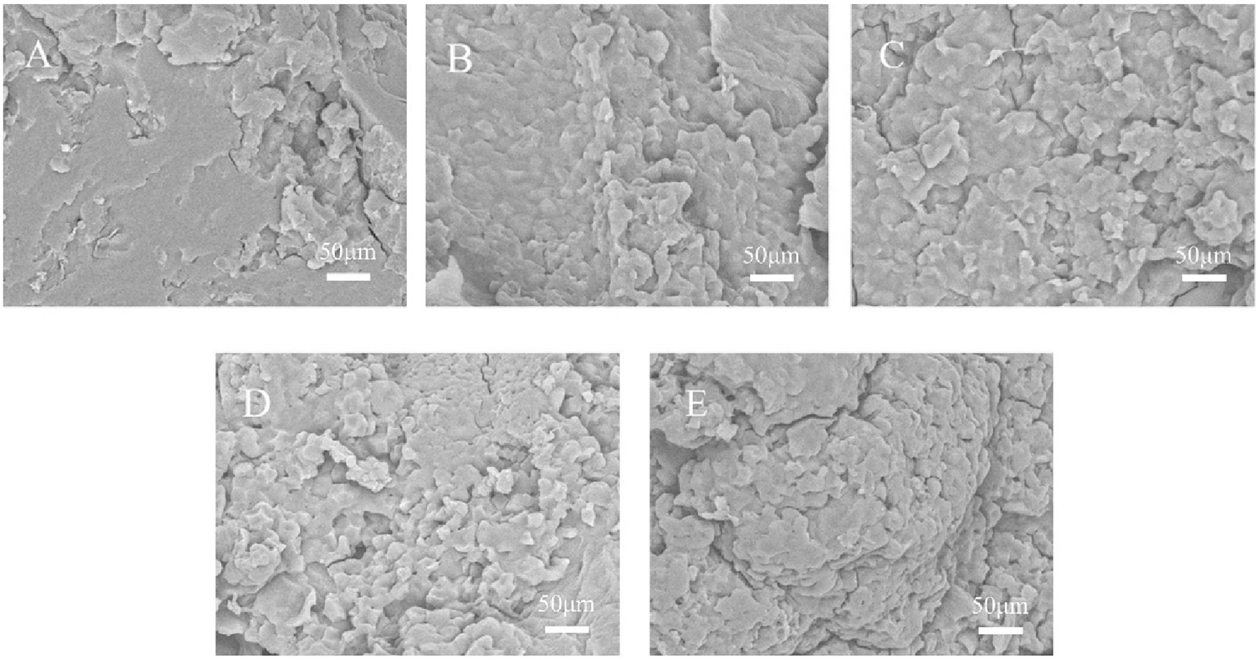

Fig. 6. Scanning electron micrographs (×1000) of rice cakes. A, B, C, D, and E represent rice cakes prepared with PC powder of 0, 10, 20, 30, and 40%, respectively.

promote the breakdown of metabolites and regulate the intestinal microbiota (Li et al., 2023).

3.8. SEM of rice cakes

The microstructure of rice cakes is shown in Fig. 6. The PC rhizomes used to make the samples were crushed and sieved through a 60 mesh sieve，The surface of the rice cake samples of the control was relatively smooth. However, the rice cakes displayed a bumpy surface with a regular pattern in the presence of PC. In addition, a number of granular microstructures were observed on the surface. In a study of sucrose on angel food cake, it was found that the starch paste and protein denaturation that occurs in the cake during heating is related to the final structure of the cake (Yang & Foegeding, 2010). The gelatinization of the starch in rice cakes may be altered in the presence of some cellulose, semi-cellulose, and lignin from the epidermis of PC (Shi et al., 2023). In the control group, the high content of starch and a high degree of gelatinization may result in a large degree of intermolecular cross-linking of starch particles, forming a smooth surface. Xiong et al. discovered that hydrogen bonds or other non-covalent interactions facilitated the adsorption of PC polysaccharide molecules on the surface of starch granules inside a starch gel (Xiong et al., 2023). The change in the microstructure of rice cakes was in line with the variation in cooking loss of the rice cakes.

4. Conclusion

The incorporation of PC powder into rice cakes altered the appearance and texture of the rice cakes, resulting in a decrease in hardness and adhesion, and a yellowish appearance. The addition of PC also altered the microstructure of the rice cakes, with the formation of a granular microstructure within the rice cakes. Rheological analysis showed that the rice cakes prepared with PC exhibited weak-gel behavior. The addition of PC powder into rice flour effectively inhibited the aging of rice cakes and the hardness of rice cakes containing PC was significantly lower than that of the control group after storage at low temperatures. PC also inhibited starch digestion, thus reducing the eGI level. In addition, the incorporation of an appropriate amount of PC powder in rice cakes endowed the products with a unique yellow color and a featured aroma of rice/PC with high-quality acceptability. Therefore, the addition of PC into rice cakes made from japonica rice flour can enrich its products, which can expand the development of the PC industry.

CRediT authorship contribution statement

Tian Zheng: Writing – original draft. **Huiyun Chen:** Supervision, Investigation, Formal analysis. **Yuanguo Yu:** Supervision, Project administration, Funding acquisition. **Pan Wang:** Supervision, Investigation, Formal analysis. **Yongxin Li:** Data curation. **Gang Chen:** Writing – review & editing, Supervision, Conceptualization. **Jinping Si:** Writing – review & editing, Project administration, Conceptualization. **Huqing Yang:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.fochx.2024.101370.

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