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Exploring the potential of bacterial cellulose paste as a fat replacer for low-fat plant-based hamburger patties

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ABSTRACT

Plant-based hamburger patties (PHPs) with reduced fat content made using fat replacers will meet the consumption goals of individuals who consume meat alternative products for health. In this study, we developed a dual-alternative food model by analysing the applicability of bacterial cellulose paste (BCP) as a fat replacer and supplementing it in PHPs. BCPs were prepared with solid contents of (w/w; 1.0%, 1.5%, 2.0%, 2.5%, and 3.0%) and compared and analyzed with three types of conventional vegetable [coconut oil, margarine, and shortening (SH)] and animal fats (beef tallow, butter, and lard) for various characteristics (appearance, dimensional stability, hardness level, and rheological properties). According to the results, BCP with a solid content of 3.0% (w/w) had the most similar characteristics to SH. Therefore, using SH as a control fat, PHPs in which 0%, 25%, 50%, 75%, and 100% (w/w) SH were replaced by 3.0% (w/w) BCP were prepared. Analysis of the appearance, instrumental color, diameter reduction, thickness, cooking loss, and texture profile of the PHPs, confirmed that replacement of 25%–50% (w/w) SH with 3.0% (w/w) BCP in the preparation of PHP resulted in i) redder color, ii) better dimensional stability, iii) lower cooking loss, and iv) higher chewiness of the final products. The results of the sensory evaluation showed that the PHPs, with 25%–50% (w/w) SH replaced with 3.0% (w/w) BCP, exhibited no significant differences ($p < 0.05$) in overall preference scores compared to the full-SH sample. In conclusion, this study demonstrated the potential of BCP as a fat substitute for the production of PHPs.

1. 1. Introduction

Many people consider meat alternative products a dietary option to pursue a healthier lifestyle. However, it is important to note that the calorie content of meat alternative products is not necessarily lower than that of real meat. Vegetable fats and oils, such as cocoa butter, coconut oil, canola oil, and sunflower seed oil, are used as fat sources to replicate the juiciness and texture of real meat (Yang et al., 2023). The use of these fats and oils increases the calorie content of meat alternative products. The high calorie content of meat alternative products makes them incompatible with the consumption goals of those who consume them for health benefits. Therefore, it is necessary to reduce the calories in alternative meat products, and a potential solution is to use fat replacers. Surprisingly, to our best knowledge, there were little attempts to apply fat replacers in meat alternative products.

Fat replacer is a substance that can provide some or all of the physiochemical and organoleptic properties of fat while having lower calories than fat (Syan et al., 2022). Fat replacers are commonly categorized based on their compositions into three groups: carbohydrate-based, lipid-based, and protein-based (Yu et al., 2021). In our research, we devised a method to utilize bacterial cellulose as a raw material for carbohydrate-based fat replacer.

Bacterial cellulose (BC) is an edible biopolymer synthesized by the fermentation of acetic acid bacteria (Gorgieva Jančič, Cepec, & Trček, 2023). BC is commonly known as 'nata de coco' in the food industry and is widely available. Nata de coco is synthesized in a liquid culture medium containing coconut water and prepared by cutting BC into cubes and then immersing them in sugar syrup. Besides being consumed as a dessert on its own, nata de coco can also be added to beverages, yogurts, and jellies to impart a chewy texture (Azeredo, Barud, Farinas,

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Vasconcellos, & Claro, 2019). The paste prepared by grinding BC, known as BC paste (BCP), has an extremely slippery texture and a milky-white appearance, similar to that of fat. Therefore, bacterial cellulose paste has sufficient potential to be used as a fat replacer.

Already a few studies have been conducted using BCP as a fat replacer in sucuk (a spicy fermented sausage made from beef or lamb) (Akoğlu, Çakır, Akoğlu, Karahan, & Çakmakçı, 2015), fish sausage (Oliveira, Guimaraes, Furtado, & Mesquita, 2022), and ice cream (Guo et al., 2018). However, as mentioned earlier, there is currently limited research on the application of BCP in meat alternative products. Therefore, in this study, we aimed to apply BCP as a fat replacer in plant-based hamburger patties (PHP), the most common type of meat alternative product. Thus, we propose a dual alternative food model by modeling meat alternative products incorporating a fat replacer.

The most obvious advantage of replacing existing fat with BCP in the production of PHPs is that the calorie and fat content of the products can be reduced. In addition, to further investigate the additional advantages associated with replacement, this study investigated how the quality characteristics of the PHPs changed when fat was replaced with BCP at various ratios. Sensory evaluations were conducted on PHPs where part of the fats was replaced with BCP and control PHP without replacement, aiming to assess differences in their organoleptic characteristics.

The study had four specific objectives: i) producing BCPs with varying solid content (1.0%, 1.5%, 2.0%, 2.5%, and 3.0%); ii) comparing and analyzing the optical, rheological, and mechanical characteristics of BCPs with those of conventional fats (three types of vegetable and animal fats) and selecting a vegetable fat that closely resembled BCP in terms of properties; iii) developing PHPs using the selected vegetable fat as a fat source and assessing the optical, physicochemical, and textural properties of the PHPs, where a portion [25%, 50%, and 75% (w/w)] or the entirety (100%, w/w) of the fat was replaced with BCP; iv) determining the optimal replacement ratio preferred by consumers through sensory evaluation.

2. Materials and methods

2.1. Preparation of bacterial cellulose pastes

Commercial BC, known as nata de coco (cubic shape; 5 mm × 5 mm × 5 mm; Gomawo Nata De Coco 5 mm; Daejin MS Inc., Seoul, Korea), was washed using the procedures suggested by Sai et al. (2020) with some modifications. First, nata de coco was rinsed several times with tap water to remove the sugar syrup on its surface. Then, the BCs were boiled at 80 °C for 30 min to eliminate the sugar syrup inside their inner matrix, immersed in cold tap water for cooling, and finally re-washed with distilled water (DW). Afterward, to confirm whether the sugar syrup on the surface and inside of nata de coco had been completely removed, the nata de coco was wrapped in gauze, squeezed to extract juice, and the sugar content in the juice was measured using a Brix refractometer (SUGAR-2PLUS; CAS Co., Yangju, Korea). As a result, unlike the initial sugar content of nata de coco, which was at 14.4% Brix, the sugar content of nata de coco measured 0.0% Brix after the removal of the sugar syrup. This value was equivalent to the Brix level of DW. Therefore, it was confirmed that the sugar syrup had been successfully removed from the nata de coco through the series of processes described above.

The BCs were then drained into a colander for 30 min and ground for 10 min using a blender (SMFP-30000, Hanil Electronic Co., Bucheon, Korea) to create a slurry. BC slurry (BCS) has a liquid-like consistency owing to its relatively low solid content, which makes it unsuitable for fat simulation. Therefore, the BCS was dewatered by vacuum filtration to generate a BC paste (BCP) with a solid content of more than 3%. Fig. 1 shows the appearance of nata de coco, BCS, and BCP. The final solid content of BCP was adjusted to 1.0%, 1.5%, 2.0%, 2.5%, and 3.0% (w/w) by adding DW to the resulting BCP and was labelled 1.0%BCP, 1.5%BCP, 2.0%BCP, 2.5%BCP, and 3.0%BCP, respectively. In addition, the BCPs were prepared for at least 24 h before use in the experiments to ensure even moisture distribution.

2.2. Preparation of conventional fats

BCP is a semi-solid material with plasticity. Therefore, the conventional fats prepared for comparison with BCP were also semi-solid fats. The final goal of this study was to explore whether BCP could be utilized as a fat replacer in the production of PHPs. It is reasonable to compare the properties of BCP only with vegetable fats, as vegetable fats are used in the production of PHPs. However, to assess the potential utilization of BCP as a fat replacer in future processed meat product manufacturing—namely, as a substitute for animal fat—BCP was also compared with animal fats. Three types of vegetable and animal fat products were used as conventional fats. Specifically, coconut oil (CO; Topwil Purified Organic Coconut Oil; Sanmik Food Ltd., Bella Vista, Australia), margarine (MA; I Can't Believe It's Not Butter!; Unilever PLC, London, England), and shortening (SH; Crisco All-Vegetable Shortening; B&G Foods

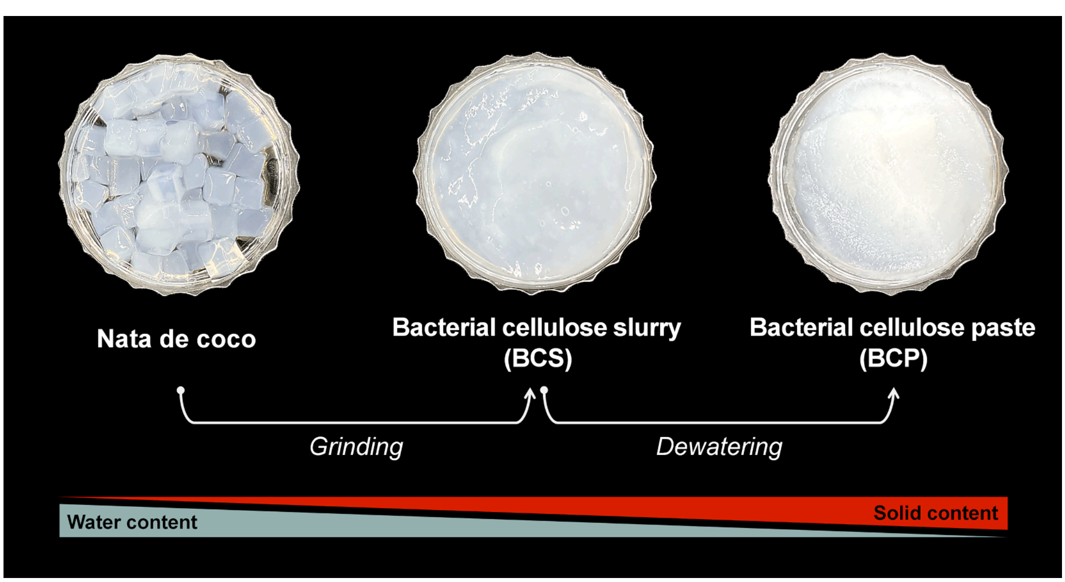

Fig. 1. Visual appearance of (**A**) nata de coco, (**B**) BCS, and (**C**) BCP. BCS: bacterial cellulose slurry; BCP: bacterial cellulose paste.

Inc., Parsippany, NJ, USA) were prepared as vegetable fats. As animal fats, beef tallow (Snowflake Beef Tallow; Hans Meat Co., Daegu, Korea), butter (BU; Anchor Unsalted Butter; Fonterra Foodservices Inc., Rosemont, IL, USA), and lard (LA; Daejeo King Lard Oil; Hans Meat Co., Daegu, Korea) were prepared.

2.3. Ingredients for the preparation of plant-based hamburger patties containing bacterial cellulose paste as a fat replacer

The ingredients used in the preparation of PHPs were entirely plant-based. The detailed information on the ingredients is as follows. Two types of textured soy proteins were used to mimic ground beef: globular-type (2–8 mm; Hokyoung Textured Soy Protein R; Hokyoung-Tech Co., Anseong, Korea) and chip-type (2–8 mm; Hokyoung Textured Soy Protein FM; Hokyoung-Tech Co., Anseong, Korea). The reason for using a combination of two types of textured soy proteins was to impart a diverse texture to final products. Simultaneously, this approach aimed to increase their density by filling the space between the globular-type textured soy proteins with chip-type ones. Methylcellulose (Methocel MX; Dow Inc., Midland, MI, USA), pea protein isolate (Empro E 86 HV Pea Protein; Emsland-Stärke GmbH, Emlichheim, Germany), and potato starch (Potato Starch Powder; Ddureban, Goyang, Korea) were used as binder. Binders fill the gaps between textured soy proteins while simultaneously fixing them in the patty matrix, preventing the patty from collapsing or disintegrating during cooking. Salt (Natural Premium Salt; CJ Cheiljedang Co., Seoul, Korea), sugar (Beksul White Sugar; CJ Cheiljedang Co., Seoul, Korea), monosodium glutamate (Miwon; Daesang Co., Seoul, Korea), garlic powder (Midum Garlic Powder; Hongseong Food; Gangwon, Korea), onion powder (Midum Onion Powder; Hongseong Food), and black pepper powder (Black Pepper Powder; Ottogi Co., Ltd., Seoul, Korea) were used as seasonings. Beet red powder (Beet Red 30; ES Food Co., Gunpo, Korea) and caramel color (Caramel; Ddureban, Goyang, Korea) were used as colorants to mimic the reddish-brown color of raw beef. Among the various concentrations (1.0%, 1.5%, 2.0%, 2.5%, and 3.0%, w/w) of BCP, the sample with characteristics most similar to conventional vegetable fats was used as a fat replacer, while one type of vegetable fat exhibiting the highest overall similarity to BCP was used as the actual fat.

2.4. Characteristics of bacterial cellulose pastes and conventional fats 8 7

2.4.1. Analysis of appearance and dimensional stability

To simultaneously present the dimensional stability of the BCPs and conventional fats, the method proposed by Kim, Bae, and Park (2017) was used with slight modifications. Dimensional stability analysis was conducted to provide visual and numerical data on how each sample would deform due to its inherent fluidity and gravitational action under identical conditions. Fig. 2 shows a schematic of the corresponding test. A cylindrical mould (28 mm inner diameter × 77 mm height) was filled with BCPs or fat to a height of 75 mm and covered with a plate (28 mm diameter × 2 mm thickness, 0.9 g) to demould the fillers without deforming their upper surface. After demoulding, all samples were left undisturbed for 30 min at room temperature (RT; 21 ± 1 °C) and photographed using an iPad (iPad Air, 4th Generation; Apple Inc., Cupertino, CA, USA) against a black background in a photo box (Daehan Co., Osan, Korea) with the aid of an LED light source. The degree of deformation was determined as the reduced height according to Eq. (1). A lower degree of height deformation suggests that the samples are more dimensionally stable. Cocoa butter (CB; Europe Chocolate Company NV, Malle, Belgium) was used as the control sample because it is solid at RT and does not deform.

$$\text{Degree of deformation(cm)} = \text{Reduced height of the sample at30min after demoulding} \quad (1)$$

2.4.2. Analysis of hardness level

The hardness level of 3.0%BCP and conventional fats was measured using previously reported methods of Wen et al. (2021) with slight modifications. 3.0%BCP and conventional fats were filled into silicone moulds (BH Silicone Ice Tray 15 Holes; Asung Daiso Co., Seoul, Korea) to form cubes (3 cm × 3 cm × 3 cm). Prior to filling the moulds, all fats were slightly warmed and stirred to ensure good fluidity and prevent the formation of empty spaces. The samples were frozen at −18 °C for 30 min before being demoulded. Then, they were stored at 4 °C for more than 24 h and the hardness was analyzed using a texture analyzer (TA-XT plus, Stable Micro System Ltd., Godalming, UK) equipped with a cylindrical aluminium probe (P/35; 35 mm in diameter). The test conditions were as follows: pre-test speed, 2 mm/s; test speed, 2 mm/s; post-test speed, 5 mm/s; strain, 50%; and trigger force, 10 g. The analyses were carried out with three replicates ($n = 3$) for each sample.

2.4.3. Analysis of rheological properties

The rheological properties of the samples were performed by referring to method of Park et al. (2023). The rheology of BCPs and conventional fats was evaluated using a frequency sweep test with a modular compact rheometer (MCR 302, Anton Paar GmbH, Graz, Austria) equipped with a parallel-plate measuring system (PP25; 25 mm in diameter). The plate system had a 1 mm gap, and the temperature was maintained at 20 °C throughout the experiment. Before the frequency sweep test, an amplitude sweep test was performed to determine the limit of the linear viscoelastic region, which was set at a shear strain of 0.01%. The angular frequency range was 0.1 to 100 rad/s. Measurements included the storage modulus (G'), loss modulus (G''), loss factor (tan δ), and complex viscosity (η^*) through the frequency sweep test.

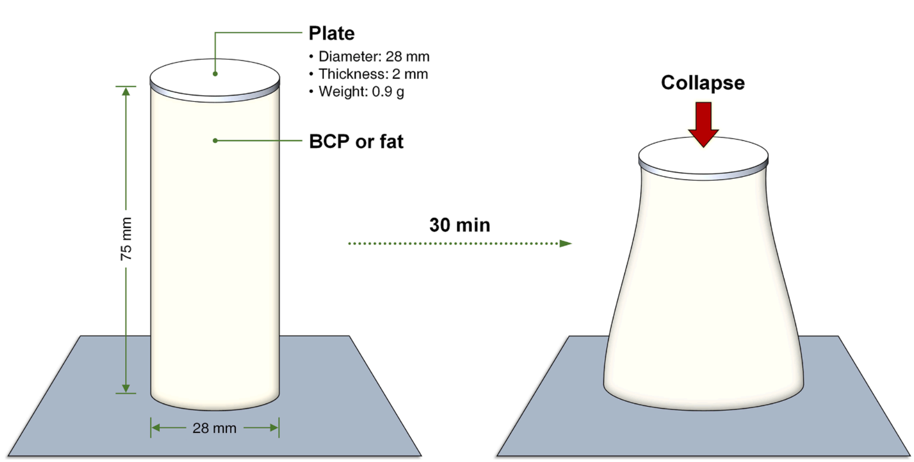

Fig. 2. Schematic diagram of the assessment method for appearance and dimensional stability of BCPs and conventional fats. BCP: bacterial cellulose paste.

2.5. Preparation of plant-based hamburger patties containing bacterial cellulose paste as a fat replacer

The ingredients used and their formulations are listed in Table 1, established through several rounds of preliminary tests. First, globular and chip-type textured soy proteins were mixed in a 1:1 (w/w) ratio and hydrated in DW at RT for 30 min. Excess water in the textured soy protein mixture was removed to adjust its weight to three times the initial dry weight. To prepare a co-colorant ant mixture mimicking the color of real beef patties, beet red powder and caramel were added to DW and stirred for 10 min. Half of the co-colorant mixture was added to the hydrated, textured soy protein mixture for dyeing, while the other half was used to prepare the methylcellulose foam. The methylcellulose foam was prepared by blending methylcellulose and a co-colorant using a hand blender (HR1622; Koninklijke Philips N.V., Amsterdam, Netherlands) until a homogeneous foam was formed. For the seasoning, salt, sugar, monosodium glutamate, garlic powder, onion powder, and black pepper powder were mixed. Finally, the colored and hydrated textured soy protein mixture, methylcellulose foam, pea protein isolate, potato starch, seasoning mixture, fat, and BCP were kneaded for 5 min using a standard mixer (KitchenAid 5K45SS; Whirlpool Co., Harbor, MI, USA). The PHPs in which 0%, 25%, 50%, 75%, and 100% (w/w) conventional vegetable fat were replaced with BCP were designated as PHP0, PHP25, PHP50, PHP75, and PHP100, respectively. The complete patty mixture was placed into circular moulds (86 mm in inner diameter and 17 mm inner depth) of 100 g each. Then, they were frozen at −18 °C for over than 24 h and demoulded.

2.6. Cooking of plant-based hamburger patties containing bacterial cellulose paste as a fat replacer

The frozen PHPs were grilled in an electric oven (EON-C503F; SK Magic Co., Ltd., Seoul, Korea) preheated to 180 °C for 15 min on the front and 10 min on the back. The internal temperature of cooked PHPs measured with a needle probe thermometer (WPT-1; CAS Co., Ltd., Yangju, Korea) was approximately 75 °C.

2.7. Characteristics of plant-based hamburger patties containing bacterial cellulose paste as a fat replacer

2.7.1. Analysis of appearance before and after cooking

Raw and cooked PHPs were photographed from the top-front, top, front, and cross-sectional views using an iPad (iPad Air 4th Generation; Apple Inc., Cupertino, CA, USA). All images were captured against a black background inside a photobox illuminated with an LED light source.

2.7.2. Analysis of instrumental surface color before and after cooking

The surface color of the PHPs was assessed according to the method reported by Lee, Lee, and Han (2018) with appropriate modifications, using a colorimeter (CR-400; Konica Minolta Sensing, Inc., Osaka, Japan) calibrated with a standard white plate ($Y = 93.8$, $x = 0.3131$, and $y = 0.3191$). The PHPs were placed on a 10-layer white paper, and the CIELAB color space (L^*, a^*, and b^*) was measured at ten randomly selected locations ($n = 10$) in each PHP. The total color difference (ΔE^*), hue angle ($H°$), and chroma (C^*) were calculated using Eqs. (2)–(4).

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (2)$$

where $\Delta L^* = L^*_{sample} - L^*_{PHP0}$, $\Delta a^* = a^*_{sample} - a^*_{PHP0}$, and $\Delta b^* = b^*_{sample} - b^*_{PHP0}$.

$$\begin{aligned} H^\circ &= \tan^{-1}(b^*/a^*),\ \text{when } a^* > 0 \text{ and } b^* > 0 \\ H^\circ &= 180^\circ + \tan^{-1}(b^*/a^*),\ \text{when } a^* < 0 \\ H^\circ &= 360^\circ + \tan^{-1}(b^*/a^*),\ \text{when } a^* > 0 \text{ and } b^* < 0 \end{aligned} \quad (3)$$

$$C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (4)$$

2.7.3. Analysis of diameter reduction, thickness, and cooking loss after cooking

Each PHP was cut in half, and the thickness and diameter of the cross sections were measured. Six samples were used for this analysis, resulting in thirty measurements ($n = 30$) of thickness and six measurements ($n = 6$) of diameter. The reduction in the diameter was calculated using Eq. (5) as suggested by Ribeiro et al (2021).

Table 1
Formulations of PHPs.

Classification	Ingredients (%, w/w)	Sample				
		PHP0	PHP25	PHP50	PHP75	PHP100
Textured soy protein mixture	Globular-type textured soy protein (hydrated)			31.1		
	Chip-type textured soy protein (hydrated)			31.1		
Colorant mixture	Red beet powder			1.2		
	Caramel color			0.6		
	Water			14.1		
Binder	Methyl cellulose			1.2		
	Pea protein isolate			2.5		
	Potato starch			2.5		
Seasoning mixture	Salt			0.4		
	Sugar			1.2		
	Monosodium glutamate			0.2		
	Garlic powder			0.2		
	Onion Powder			0.2		
	Black pepper powder			0.1		
	Potato starch			0.6		
	Methyl cellulose			14.1		
Conventional fat or fat replacer	Fat (SH)	13.2	9.9	6.6	3.3	0
	BCP	0	3.3	6.6	9.9	13.2
Total				100		

PHP: plant-based hamburger patty; SH: shortening; BCP: bacterial cellulose paste.

$$\text{Diameter reduction}\,(\%) = \left(\frac{D_r - D_c}{D_r}\right) \times 100\% \quad (5)$$

where D_r the diameter (mm) of raw PHPs (86 mm) and D_c the diameter (mm) of cooked PHPs.

The cooking loss of PHPs was determined by measuring the weight difference before and after cooking, as described in Eq. (6) proposed by Ribeiro et al (2021).

$$\text{Weight loss}\,(\%) = \left(\frac{W_r - W_c}{W_r}\right) \times 100\% \quad (6)$$

where W_r the weight (mg) of raw PHPs and W_c the weight (mg) of cooked PHPs.

2.7.4. Analysis of texture profile after cooking

The texture profile of cooked PHPs was analyzed using the method suggested by Lee, Choi, and Han (2022) with minor modifications. Cooked PHPs were cut into cuboids (2 cm × 2 cm × 1 cm). Texture profile analysis of cooked PHPs was conducted using a texture analyzer (TA-XT Plus, Stable Micro System Ltd., Godalming, UK) equipped with a cylindrical aluminium probe (P/35; ∅ 35 mm). The testing conditions were as follows: pre-test speed, 3 mm/s; test speed, 2 mm/s; post-test speed, 2 mm/s; strain, 50%; trigger force, 20 g; time interval between the two compressions, 3 s. The analyses were performed with five replicates ($n = 5$) for each sample.

2.8. Sensory evaluation of cooked plant-based hamburger patties containing bacterial cellulose paste as a fat replacer

Sensory attributes of cooked PHPs, including shape, color, gloss, aroma, flavor, oiliness, tenderness, chewiness, juiciness, and overall preference, were evaluated by a 25-member untrained panel with a 9-point hedonic scale (1 = dislike extremely to 9 = like extremely). In order to investigate general consumer preferences for PHPs with fat replacers applied, untrained panels were used. The panels consisted of 6 male and 19 female graduate students aged between 21 and 32, from the College of Life Sciences and Biotechnology at Korea University (Seoul, Korea). The panel was given two types of samples: an uncut whole circular PHP (ø 77–79 mm) for evaluating shape, color, and gloss; a cut square PHP (25 × 25 mm) for evaluating aroma, flavor, oiliness, tenderness, chewiness, and juiciness post-consumption. Samples were assigned a 3-digit random code for anonymity. The test was performed in a laboratory area illuminated by white fluorescent lights. Plain crackers and water were provided as palate cleansers to the panels in between evaluations to remove residues and aftertaste of previous samples in the mouth.

2.9. Statistical analysis

Statistical analyses were performed using the IBM SPSS Statistics 27 software (SPSS Inc., Chicago, IL, USA). Significant differences ($p < 0.05$) among the samples were determined using one-way analysis of variance, followed by Duncan's multiple range test. Data are presented as mean ± standard deviation.

3. Results and discussion

3.1. Characteristics of bacterial cellulose pastes and conventional fats

3.1.1. Appearance and dimensional stability

Fig. 3 shows the appearance of the sample and the degree of height deformation after the sample was removed from the cylindrical mould and left for 30 min. A lower degree of height deformation indicates higher dimensional stability of the samples (Kim et al., 2017). BCP was milky white and exhibited the characteristic gloss of conventional fat. Therefore, the appearance of BCP was similar to that of CO, SH, BT, and LA, with a milky white color. The remaining MA and BU samples were pale yellow in color. BT is naturally yellow due to the β-carotene present in milk fat. MA, an imitation of BT, contains artificially added β-carotene as a coloring agent to mimic the color of BT (Fruehwirth et al., 2021). Therefore, the addition of a yellow pigment to prepare a BCP-based BT substitute is necessary. However, since BCP is a suspension of BC dispersed in water, lipid-soluble pigments such as β-carotene cannot be used to mimic the yellow color of BT. Instead, water-soluble yellow pigments are used.

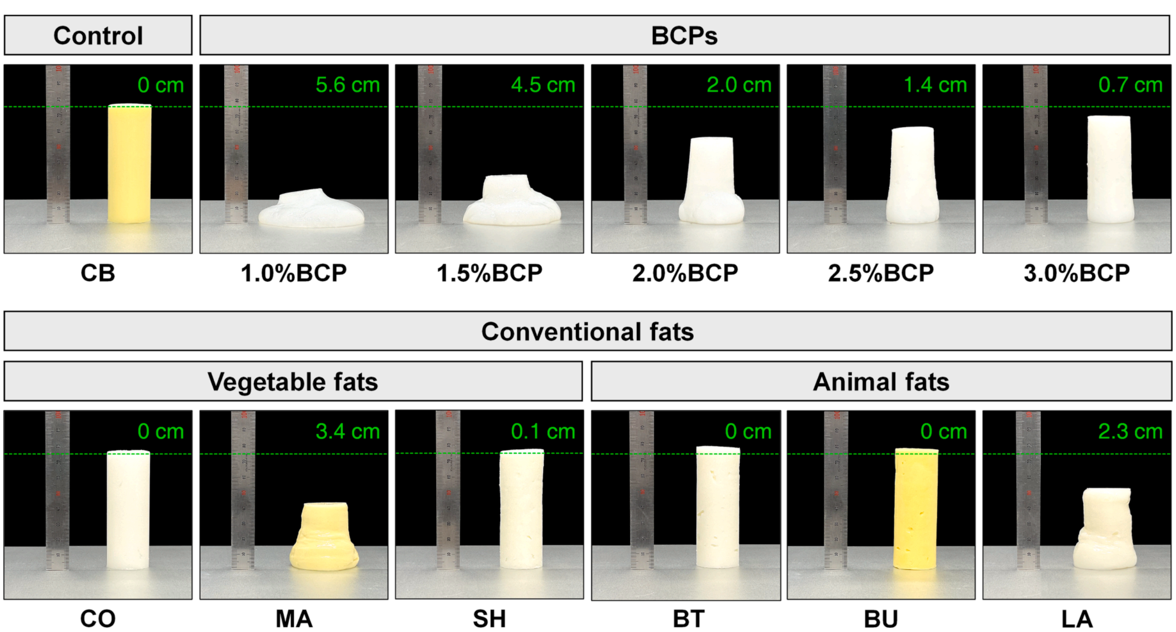

Fig. 3. Appearance and dimensional stability of BCPs at various solid contents [1.0%, 1.5%, 2.0%, 2.5%, and 3.0% (w/w)] and conventional fats. The green dotted line represents the height of the CB as a control sample, which remains unchanged due to its non-fluid state at the experimental temperature (21 ± 1 °C). The values highlighted in green represent the degree of deformation for each sample. BCP: bacterial cellulose paste; CB: cocoa butter; CO: coconut oil; MA: margarine; SH: shortening; BT: beef tallow; BU: butter; LA: lard.

The degree of deformation values of the samples was as follows: 1.0%BCP (5.6 cm) > 1.5%BCP (4.5 cm) > MA (3.4 cm) > LA (2.3 cm) > 2.0%BCP (2.0 cm) > 2.5%BCP (1.4 cm) > 3.0%BCP (0.7 cm) > SH (0.1 cm) > CO, BT, and BU (0 cm). The dimensional stability of the BCPs increased with solid content. Therefore, the BCP sample with the highest dimensional stability was 3.0%BCP. Among the plant-based fats, CO and SH showed the most comparable dimensional stability to 3.0%BCP, and MA to 1.5%BCP. Among the animal-based fats, BT and BU showed dimensional stability most similar to that of 3.0%BCP, and LA to that of 2.0%BCP. These results suggest that different types of fat can be mimicked by BCPs depending on their solid content, which can be one of the functional advantages of using BCPs as fat replacers. In conclusion, it was established that 3.0%BCP had the highest similarity to conventional fat in terms of dimensional stability.

3.1.2. *Hardness level*

The hardness of fat greatly enhances its practical use by providing information about its workability and functionality. Additionally, it also affects the organoleptic properties of the final products, particularly the texture and mouthfeel (Gao, Gao, Yang, Liu, & Wang, 2022). Therefore, most studies on fat substitutes have taken into account the hardness measurements.

Fig. 4 shows the hardness of 3.0%BCP and conventional fats; the values were significantly different ($p < 0.05$) among the samples. Animal fats exhibit a relatively higher hardness than vegetable fats. This is because animal fats h contain more saturated fatty acids than vegetable fats (Giakoumis, 2013). In general, the hardness of fats is proportional to their saturated fatty acid content (Lapčíková, Lapčík, Valenta, & Kučerová, 2022). Saturated fatty acids form a dense and rigid matrix owing to their linear chain structures without double bonds. In contrast, unsaturated fatty acids generate a loose and flexible matrix because of their bent (nonlinear) chain structures (Pande & Akoh, 2016). Thus, fatty acids in animal fats are packed more tightly than those in vegetable fats, resulting in a harder texture. However, as an exception, CO exhibited higher hardness than BU and LA. This is because the saturated fatty acid content of CO is approximately 92%, which is much higher than that of other typical vegetable fats (Deen et al., 2021). The CO used in this analysis has a saturated fatty acid content of 91.7%.

The hardness value of the fat the replacer, 3.0%BCP, was 3.08 ± 0.05 N, which was most similar to MA (3.10 ± 0.04 N) and lower than SH (15.84 ± 0.10 N). Although the network density of BCP is increased by the content of cellulose, it is important to note that BCP is a hydrocolloid with a large amount of water in its matrix (Zhao, Khalesi, He, & Fang, 2023). MA is a water-in-oil emulsion. The moisture and oil contents of MA varied among products, but the MA used in this study contained 52% (w/w) moisture and 45% (w/w) vegetable oil. In other words, due to the relatively high moisture content of MA compared to other fats, it had a relatively lower hardness than the other fats.

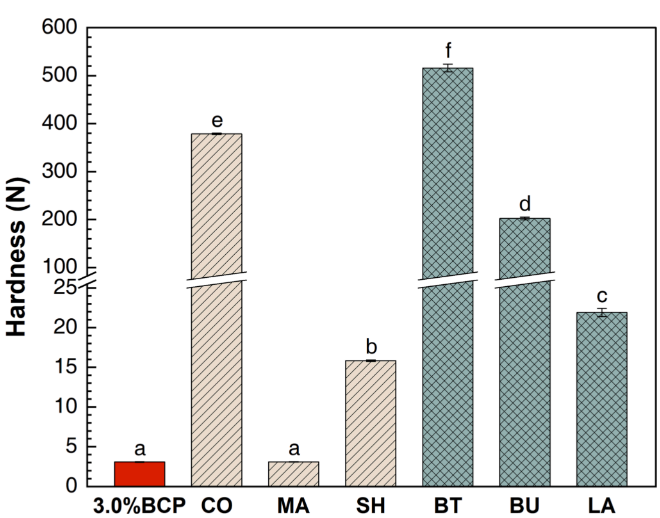

Fig. 4. (**A**) Storage modulus (G'), (**B**) loss modulus (G''), (**C**) loss tangent (tan δ), and (**D**) complex viscosity (η^*) of BCPs at different solid contents [1.0%, 1.5%, 2.0%, 2.5%, and 3.0% (w/w)] and conventional fats according to angular frequency (ω). BCP: bacterial cellulose paste. CO: coconut oil; MA: margarine; SH: shortening; BT: beef tallow; BU: butter; LA: lard.

3.1.3. *Rheological properties*

Hardness measurement is a simple experimental technique that can be used to analyze and compare the functionality of fat substitutes with that of conventional fats. However, this method is insufficient for investigating the fundamental characteristics of a network of samples because it completely destroys the network of the samples (Yazar & Rosell, 2022). Accordingly, the changes in rheological properties of the samples in response to angular frequency (ω) variations were additionally analyzed.

Fig. 5 shows the rheological properties of the BCPs and conventional fats. In the frequency sweep properties, two dynamic moduli [G' (Fig. 5A) and G'' (Fig. 5B)] can be obtained. The G' indicates elastic solid-like behaviour, and the G'' defines the viscous behaviour of the material. Therefore, the G' greater than G'' ($G' > G''$) indicates that the material is more similar to a solid than a liquid (Kim, Wen, Kim, & Park, 2022). All samples showed $G' > G''$ over the entire frequency range, implying that they are gel-like materials or gel. This suggests that BCPs can act as solid-like materials equivalent to solid fats in PHPs and positively affect the morphological stability of PHPs before and after cooking (Park, Lee, Kim, & Park, 2023). In other words, the BCPs effectively mimicked the solid-like behaviour of conventional solid fats. The G' value of BCPs increased as the solid content of the BCPs increased. This was because as the solid content of the BCP increased, the interactions between the BC-BC chain and the BC chain-water molecule increased, leading to a stronger BCP network structure (Javidi, Razavi, & Amini, 2019).

Tan δ is the value obtained by dividing G'' by G' (G''/G'). *Tan* $\delta > 1$ indicates that the sample predominantly displays viscous properties, whereas tan $\delta < 1$ signifies that the sample predominantly exhibits elastic properties (Li et al., 2022). As shown in Fig. 5C, the tan δ of all samples ranged from 0.1 to 0.8, indicating that the elastic properties of all samples predominated over viscous properties. The tan δ of all samples was over 0.1, which indicates solid-like behaviour (weak gel). Notably, tan δ values of CO and BT presented high-frequency dependence, a more viscous nature to elastic or a more elastic nature to viscous, respectively. The hydrogen bonds in each fat network are physical and can be broken and recombined by external stress. This indicates that a higher structural deformation was observed in CO and BT. The BCPs showed a strong frequency dependence, but exhibited a more elastic nature at higher frequencies, denoting higher structural stabilisation (Tarancón, Hernández, Salvador, & Sanz, 2015). The SH with the minor change in tan δ value maintained its elastic-like behaviour overall frequency range, which was lower or similar to the fat replacers containing higher BCP contents.

Fig. 5D shows a decrease in η^* as ω increased across all samples, indicating their typical behaviour as shear-thinning fluids (Lee, Kim, & Park, 2023). The absolute value of slope in η^* is another parameter for describing the behaviour of materials. If the value is closer to 1, it shows higher firmness of the material, ranges between 0.96 and 1.00 indicate a solid-like structure, and between 0.91 and 0.95, implying a weak gel structure (Salimi-Kenari, Mollaie, Dashtimoghadam, Imani, & Nyström, 2018). As shown in Fig. 5D, the slopes of both CO and BT were 1.00, and those of BU, SH, and 3.0%BCP were 0.96, 0.97, and 0.99, respectively. These results suggest their solidity or solid-like structures, supporting the results presented in Section 3.1.1, with little to no structural deformation owing to the high-dimensional stability of CO, SH, BT, BU, and even 3.0%BCP. In other words, 3.0%BCP, the targeted fat replacer in this study, could also contribute to retaining the PHP shape owing to its viscoelastic properties (Gibis, Schuh, & Weiss, 2015). As a control

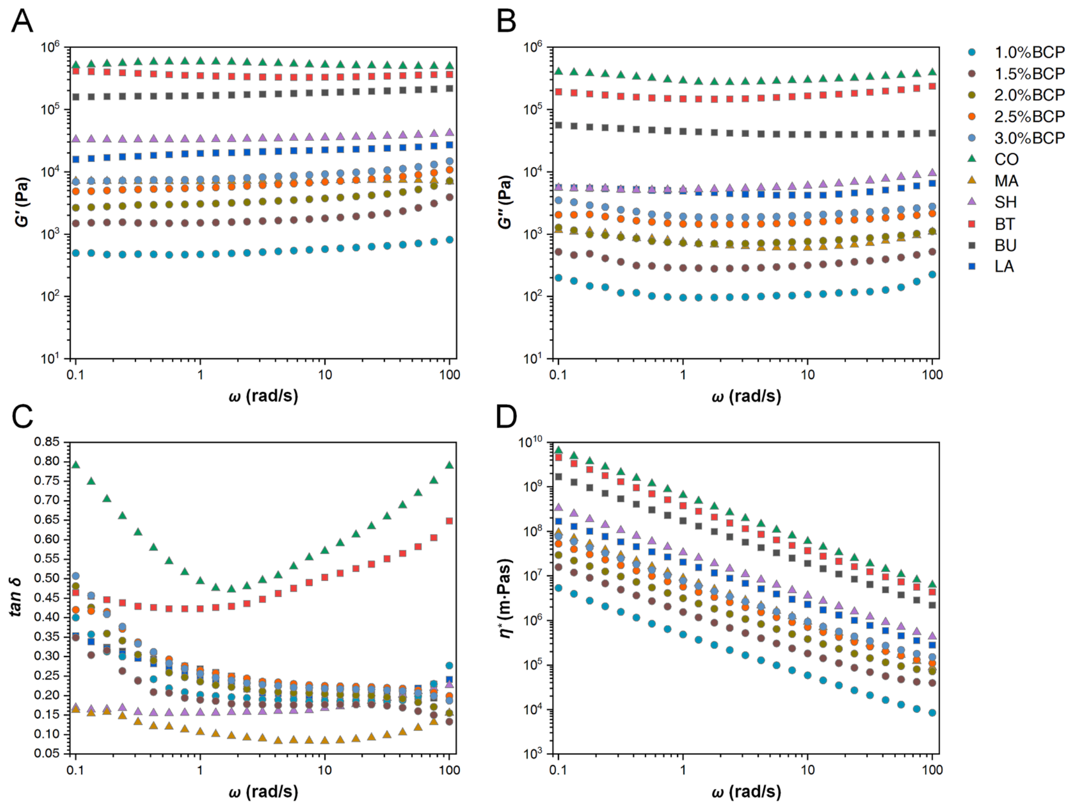

Fig. 5. Hardness of 3.0%BCP and conventional fats. The data are expressed as the mean ± standard deviation for three replicates ($n = 3$). Different lowercase letters (a–f) indicate the significant differences ($p < 0.05$) among the PHPs analyzed using Duncan's multiple range tests. CO: coconut oil; MA: margarine; SH: shortening; BT: beef tallow; BU: butter; LA: lard. Vegetable and animal fats were represented by green and beige bar graphs, respectively.

vegetable fat for the 3.0%BCP, SH was selected because of it similar characteristics of *G'*, *G"*, tan *δ*, and slope of *η** which have a more elastic nature than viscous ones. This choice also collectively considered appearance, dimensional stability, and hardness.

3.2. Characteristics of plant-based hamburger patties containing bacterial cellulose paste as a fat replacer

3.2.1. Appearance before and after cooking

Fig. 6 shows the appearance of the raw PHPs. Because the PHPs were moulded using a circular mould, all samples had the same diameter of 83 mm and thickness of 17 mm. No visual differences were observed among raw PHP0, PHP25, PHP0, and PHP75. They exhibited an opaque and pinkish-brown color similar to that of raw real meat patties, attributed to fat globules from SH being dispersed in the matrix and scattering light, resulting in opacity (Zhao, Bhandari, Gaiani, & Prakash, 2021). In other words, the effect of replacing 25%, 50%, and 75% (w/w) of SH with 3.0%BCP was not evident from the appearance of the raw PHPs. However, raw PHP100 without SH had a darker and more transparent matrix (the part that filled the spaces between the textured soy proteins in the PHP) than the other samples. The translucent matrix of raw PHP100 differed distinctly from typical raw real meat patties and directly exposed the textured soy proteins inside the sample. Therefore, PHP100 was considered to have an unfavourable external appearance.

The appearance of cooked PHPs is shown in Fig. 7. The effect of replacing SH with BCP was not apparent in the raw PHPs. However, this effect became more evident after cooking. Although all samples were cooked under the same conditions for the same amount of time, PHP0 appeared to have been overcooked, with the surface slightly burned. In addition, compared to the other samples, PHP0 exhibited a more severe shape shrinkage, resulting in a surface that was bumpy and uneven. The cross-section PHP0 showed it had less volume and a relatively loosely combined textured soy protein and matrix compared to the other samples containing BCP. This occurred because the SH that comprised the volume inside BCP0 melted and leaked from BCP0 during the high-temperature cooking process, causing the spaces previously filled with SH to turn empty, resulting in a contraction in shape (López-López et al., 2011).

PHPs containing BCP displayed a redder surface color than PHP0 and showed a bulkier shape without shrinkage. In particular, PHP25, PHP50, and PHP75, but not PHP100, showed more desirable characteristics appearance than PHP0. They exhibited a greasy, moist, and delicious-looking surface owing to the addition of SH and the excellent water-retention capacity of BCP. In contrast, the surface of PHP100 was not greasy and had a slightly matte appearance owing to the absence of added SH.

Notably, as the amount of BCP increased, the edges of the PHPs did not collapse and became more distinct. This suggests that increasing the amount of BCP improved the post-cooking stability of the PHP. A detailed explanation is provided in Section 3.2.3; however, this phenomenon is believed to occur because the BCP added to the PHPs forms a thin crust on the surface of the samples as it dries due to the heat during cooking, preventing the contraction of their shape. Overall, the replacement of BCP with SH had a positive effect by indicating superior appearance characteristics than the PHP with SH only added within the 25%–75% (w/w) range, whereas a complete (100%, w/w) replacement was undesirable.

3.2.2. Instrumental color of surface before and after cooking

Many researchers are striving to enhance the color mimicry of meat alternatives to real meat by using a combination of two or more pigments rather than relying on a single pigment. In this study, the reddish-brown color of real meat patties was replicated by incorporating red beet with a bright reddish tone and caramel color with a dark brown tone.

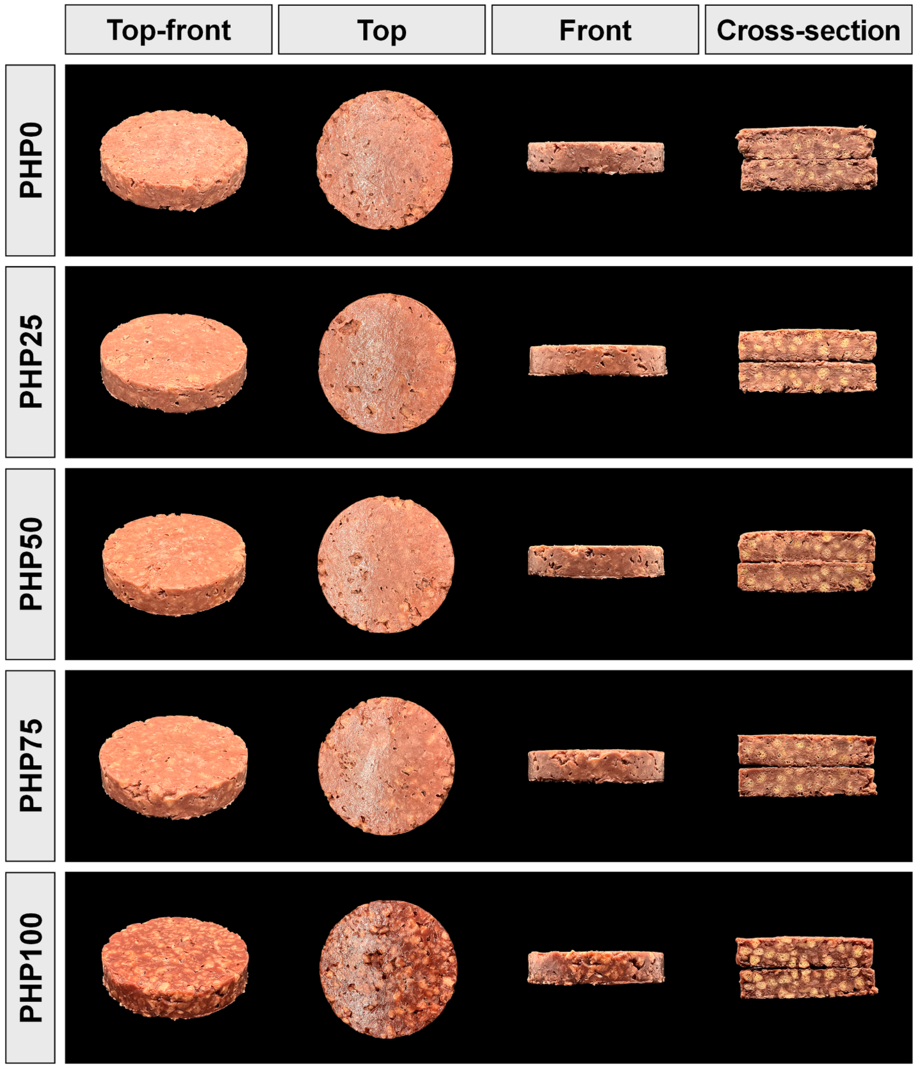

Fig. 6. Visual appearance of raw PHPs from different angles (top-front, top, front, and cross-section). PHP: plant-based hamburger patty.

Ryu et al. (2023) also concluded that when manufacturing PHPs, a combination of red beet and cocoa pigments most effectively replicates the color of cooked real meat patties.

Table 2 lists the instrumental color parameters of raw and cooked PHPs. The L^* value of raw PHPs decreased significantly ($p < 0.05$) with increasing BCP content. These results suggest that reduced SH levels decrease the lightness of raw PHPs. Fat globules in food products scatter light and increase their lightness of products (Zhao, et al., 2021). Therefore, the fat globules dispersed from the SH in the matrix of the PHPs scatter the light absorbed by the PHPs. The changes in a^* and b^* values resulting from the addition of BCP to PHP25, PHP50, and PHP75 were insignificant, and no discernible difference was observed even upon visual inspection with the naked eye. With the addition of BCP, the ΔE^* value of raw PHPs significantly increased ($p < 0.05$). The H° and C^* values of raw PHPs containing BCP showed significantly higher ($p <$ 0.05) than those of PHP0.

The L^* value of cooked PHPs was significantly lower ($p < 0.05$) than that of raw PHPs, and this value significantly decreased ($p < 0.05$) as the BCP content increased. This resulted from the carbohydrates, proteins, and lipids in the PHPs reaction to cooking heat, forming dark-colored chemical compounds. One of the most representative examples is the Maillard reaction, in which amino acids and reducing sugars interact with one another while being heated to produce brown compounds (Linghu et al., 2020). Notably, although there were few differences in the a^* and b^* values among the raw samples, these differences remarkable increased among the cooked samples. In other words, the high temperatures applied to the PHPs during cooking induced considerable differences in a^* and b^* values among the PHPs.

Cooking significantly reduced ($p < 0.05$) the a^* value of the PHPs. This was because beet red, a natural pigment in PHPs, faded and was discolored by heat. This phenomenon can be evaluated as a good representation of the color change of real meat patties from red to brown upon cooking. Thermal treatment denatures myoglobin in meat and changes its color from red to brown (Schwartz, Marais, Strydom, & Hoffman, 2022). To more effectively mimic the browning phenomenon of real meat caused by cooking, Sakai, Sato, Okada, and Yamaguchi (2022) used beet red in combination with laccase and sugar beet pectin when producing PHPs. Consequently, they successfully implemented a browning system of PHPs during cooking that closely resembles real meat patties.

The b^* value of cooked PHPs containing BCP was significantly lower ($p < 0.05$) than that of PHP0. The numerical difference between PHP0 and PHP25 was slight, but PHP50, PHP75, and PHP100 showed b^* value of 47.15%–62.36% of PHP0. This could be attributed to the fact that the Maillard reaction on the surface of the PHPs was accelerated as the SH content increased, because fat acted as a heat transfer medium, which led to an increase in yellowness (Ananey-Obiri et al., 2018; Wang, Dong, Zhang, Yu, & Wang, 2021). The Maillard reaction not only affects the browning of real meat patties during cooking but also plays a crucial role in taste and flavour by generating various volatile compounds.

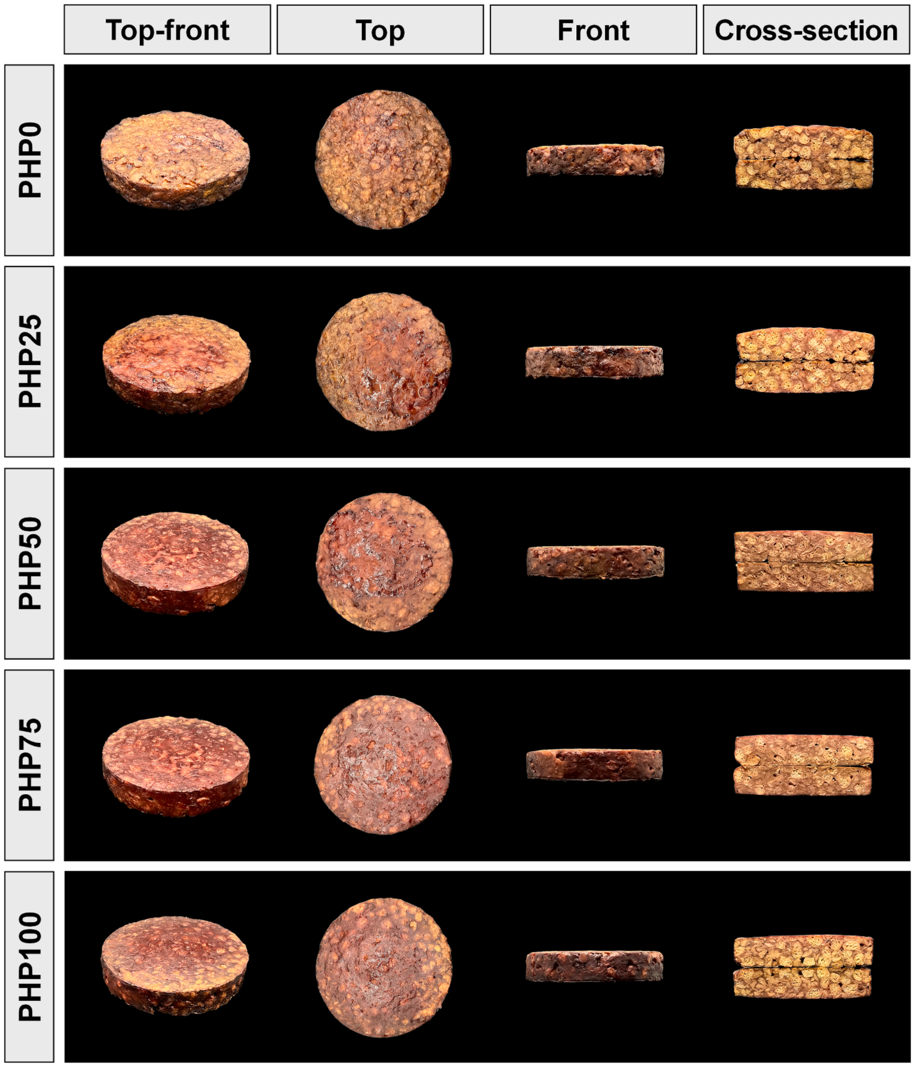

Fig. 7. Visual appearance of cooked PHPs from different angles (top-front, top, front, and cross-section). PHP: plant-based hamburger patty.

Table 2
Instrumental color parameters of raw and cooked PHPs.

State	Sample	Instrumental color parameter					
		L^*	a^*	b^*	ΔE^*	H°	C^*
Raw	PHP0	41.07 ± 0.53^{Ei}	23.44 ± 0.49^{Ae}	10.56 ± 0.42^{Ac}	–	0.42 ± 0.01^{Abc}	330.56 ± 14.39^{Ae}
	PHP25	39.99 ± 0.56^{Dh}	23.95 ± 0.50^{Be}	11.21 ± 0.62^{BCd}	1.55 ± 0.59^{Aa}	0.44 ± 0.02^{Bcd}	349.95 ± 17.26^{Cf}
	PHP50	39.15 ± 0.45^{Cg}	23.72 ± 0.47^{ABe}	11.28 ± 0.49^{BCd}	2.15 ± 0.53^{Ba}	$0.44 \pm 0.01B^{Ccd}$	$345.12 \pm 15.92B^{Cef}$
	PHP75	37.79 ± 0.77^{Bf}	23.83 ± 0.48^{Be}	11.59 ± 0.65^{Cde}	3.54 ± 0.580^{Cb}	0.45 ± 0.02^{Cd}	351.26 ± 16.96^{Cf}
	PHP100	32.21 ± 1.38^{Ad}	23.36 ± 0.70^{Ae}	11.10 ± 0.95^{Bd}	8.94 ± 1.36^{De}	$0.44 \pm 0.03B^{Ccd}$	$335.11 \pm 24.20A^{Bef}$
Cooked	PHP0	31.21 ± 1.67^{Cc}	15.12 ± 1.06^{Ab}	13.87 ± 1.23^{Df}	–	0.74 ± 0.03^{Df}	211.70 ± 31.03^{Bc}
	PHP25	32.88 ± 0.82^{De}	14.28 ± 1.14^{Aa}	12.08 ± 0.79^{Ce}	3.00 ± 0.39^{Ab}	0.70 ± 0.05^{Ce}	175.81 ± 17.60^{Aa}
	PHP50	29.51 ± 0.99^{Bb}	19.88 ± 2.13^{Cd}	8.65 ± 1.16^{Bb}	7.62 ± 1.12^{Bc}	0.41 ± 0.07^{Bb}	237.86 ± 43.77^{Cd}
	PHP75	27.73 ± 0.58^{Aa}	18.54 ± 0.84^{Bc}	6.54 ± 0.55^{Aa}	8.87 ± 0.32^{Cd}	0.34 ± 0.01^{Aa}	193.68 ± 19.30^{ABb}
	PHP100	27.96 ± 0.63^{Aa}	18.16 ± 1.05^{Bc}	6.75 ± 0.79^{Aa}	8.50 ± 0.149^{Cd}	0.35 ± 0.02^{Aa}	188.45 ± 24.07^{Aab}

Data expressed as mean ± standard deviation of ten replicates ($n = 10$).
Different uppercase letters (A–E) in the same column indicate a significant difference ($p < 0.05$) among the same state (raw or cooked) MAPs determined by Duncan's multiple range test.
Different lowercase letters (a–i) in the same column indicate a significant difference ($p < 0.05$) among the all state (raw and cooked) MAPs determined by Duncan's multiple range test.
PHP: plant-based hamburger patty.

Consequently, the induction of the Maillard reaction is essential for creating a meat-like taste and flavour during the cooking of meat alternative products. However, as indicated by the *b** value, the Maillard reaction occurred less frequently in PHP50, PHP75, and PHP100 than in PHP0 and PHP25.

The *ΔE** value of cooked PHPs increased as the BCP content increased, as in raw PHPs. The difference in *H*° value among the cooked PHP samples was greater than that in the raw PHPs. A higher *H*° value means that the color of samples is less red and more yellow (Sun, Rasmussen, Cavender, & Sullivan, 2019). In cooked PHPs, *H*° value tended to decrease as the BCP content increased, and the difference was more pronounced when the BCP content was 50% (w/w) or more.

3.2.3. Diameter reduction, thickness, and cooking loss after cooking

The reduction in diameter, thickness, and cooking loss of the PHPs are shown in Fig. 8. Interestingly, as the BCP content increased, the thickness of the PHPs tended to increase, and the reduction in diameter significantly decreased ($p < 0.05$). This is thought to occur because the BCP forms a thin crust on the outer layer of the PHPs as they dry from the cooking heat. In this study, the crust formed on the surface of PHPs cooked with BCP was named the BCP crust. The BCP crust was thin but solid, preventing the PHPs from shrinking in shape owing to cooking heat. The effect of preventing shape shrinkage of the PHPs owing to BCP formation can be visually confirmed through Fig. 7 with description in Section 3.2.1. Based on these results, it is expected that adding BCP to real meat patties can effectively prevent dimensional shrinkage. Therefore, additional follow-up research on this topic is required.

In real meat patties, muscle fibres (myofibrils) are denatured at high temperatures during cooking, which generally leads to a reduction in the diameter and thickness of the patties (Osman et al., 2022). Similar trends were observed for PHP25, PHP50, PHP75, and PHP100. This indicates that the PHP components were denatured by the cooking heat. However, in the PHP0, both diameter and thickness simultaneously decreased after cooking. This was likely because the rate of thickness reduction caused by SH leakage was greater than the rate of increase in thickness owing to diameter contraction.

Cooking loss is a crucial parameter of cooked meat products since it is directly correlated with the juiciness and yield of the final products (Gómez, Ibañez, & Beriain, 2019). Many previous studies (Bakhsh et al., 2022, Vu, Zhou, & McClements, 2022, Zhou, Vu, Gong, & McClements, 2022) have reported lower cooking losses for PHPs compared to real meat patties. It is one of the strong advantages that PHPs have over real meat patties. Interestingly, PHP25 and PHP50 indicated the lowest ($p < 0.05$) cooking loss values among all samples. The cooking loss of PHP0 was 19.69 ± 0.74%, whereas that of PHP25 and PHP50 was 15.59 ± 0.67% and 15.31 ± 0.86%, respectively. In other words, it was found that replacing 25%–50% (w/w) of SH with BCP reduces or improves cooking losses by 20.78%–22.26%. These results suggested that the optimal replacement ratio of BCP to SH was 25%–50% (w/w).

BC has an excellent water-holding capacity (Wu et al., 2021). According to Marchetti, Muzzio, Cerrutti, Andrés, and Califano (2017), when 3% (w/w) of dried bacterial nanocellulose was added to the meat sausage batter, the moisture content and water-holding capacity of the cooked sausage increased from 74.3 ± 0.2 g/100 g and 64.9 ± 0.7 g H_2O/100 g to 75.3 ± 0.2 g/100 g and 83.8 ± 0.7 g H_2O/100 g, respectively. Therefore, PHP25 and PHP50 would have considerably reduced the amount of water lost to the external environment during the high-temperature cooking process because of the excellent water-holding capacity of BCP, compared to PHP0 (without BCP). The SH contained in PHP25 and PHP50 effectively inhibited the evaporation of water from the PHPs by forming a fat layer on their surface during cooking. For PHP100, it was impossible to expect suppression of water evaporation by SH during the cooking process because PHP100 does not contain SH at all. PHP100 showed the highest cooking loss value among all samples, followed by PHP0. In other words, using a combination of SH and BCP was more effective in reducing the cooking loss of PHPs than when used alone.

Table 3
Texture parameters of cooked PHPs.

Sample	Texture				
	Hardness (N)	Springiness	Cohesiveness	Chewiness	Resilience
PHP0	18.185 ± 1.118[a]	0.180 ± 0.013[a]	0.097 ± 0.011[a]	0.321 ± 0.058[a]	0.026 ± 0.003[a]
PHP25	18.611 ± 0.618[a]	0.205 ± 0.014[a]	0.100 ± 0.012[a]	0.381 ± 0.057[a]	0.029 ± 0.003[a]
PHP50	18.525 ± 0.196[a]	0.252 ± 0.041[b]	0.124 ± 0.011[b]	0.579 ± 0.123[b]	0.035 ± 0.004[b]
PHP75	22.444 ± 0.538[b]	0.246 ± 0.010[b]	0.123 ± 0.008[b]	0.684 ± 0.075[c]	0.034 ± 0.002[b]
PHP100	24.035 ± 0.708[c]	0.247 ± 0.012[b]	0.136 ± 0.004[b]	0.804 ± 0.062[d]	0.037 ± 0.001[b]

Data expressed as mean ± standard deviation of five replicates ($n = 5$).
Different lowercase letters (a–d) in the same column indicate a significant difference ($p < 0.05$) among the PHPs determined by Duncan's multiple range test.
PHP: plant-based hamburger patty.

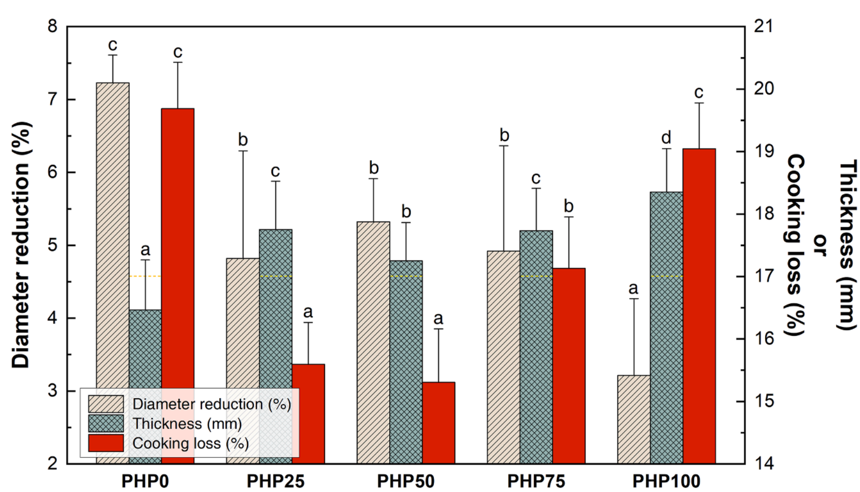

Fig. 8. Diameter reduction, thickness, and cooking loss of cooked PHP. The data are expressed as the mean ± standard deviation for six ($n = 6$), thirty ($n = 30$), and three replicates ($n = 3$) for diameter reduction, thickness, and cooking loss, respectively. The yellow dotted line on the bar indicating thickness represents the original thickness of 17 mm before cooking. Different lowercase letters (a–e) indicate the significant differences ($p < 0.05$) among the PHPs analyzed using Duncan's multiple range tests. PHP: plant-based hamburger patty.

3.2.4. Texture profile after cooking

Texture parameters, such as hardness, springiness, cohesiveness, chewiness, and resilience, resulting from the texture profile analysis, are presented in Table 3. PHP0, PHP25, and PHP50 exhibited the significantly lowest hardness ($p < 0.05$). SH and water act as plasticisers within the matrix of PHPs, causing a decrease in their hardness (Erinc, Mert, & Tekin, 2018). Therefore, the hardness values of PHP0, PHP25, and PHP50, which have relatively high SH content, were lower than those of the other PHPs.

Remarkably, there were no significant differences ($p \geq 0.05$) between PHP0 and PHP25 values for any of the parameters. These results suggest that replacing 25% (w/w) SH with BCP does not change the textural characteristics of PHPs. This is a highly encouraging research finding in the field of fat replacers, as it demonstrates the ability to achieve PHP with textural characteristics identical to those of the control, despite replacing 25% (w/w) of SH with BCP.

PHP50 exhibited the same ($p \geq 0.05$) hardness values as PHP0 and PHP25; however, the remaining parameters were significantly higher ($p < 0.05$) than those of both samples. The comparatively high chewiness of PHPs can be evaluated as a textural characteristic that better simulates real meat patties (Kim, Lee, Lee, Jo, & Choi, 2022). In addition, when looking at the dataset as a whole, the values of all parameters tended to increase as the content of the added BCP increased. This was probably because BCP strengthened the structure and stability of the PHPs by filling the voids between the textured soy proteins and interacting at molecular level with other components. Marchetti, Muzzio, Cerrutti, Andrés, and Califano (2017) also reported results similar to ours. In their study, when dried bacterial nanocellulose was added to the meat sausage batter at a rate of 1%–3% (w/w), the hardness and chewiness values of the cooked sausages increased compared to the control sample. These findings suggest that BCP has the potential to be used as a texture modifier in meat alternative products, including PHPs, by increasing the hardness, springiness, cohesiveness, chewiness, and resilience. Furthermore, it also suggested that the BCP can act as a binder to enhance the bonding among the components of the meat alternative products.

3.3. Sensory evaluation

Based on previous results, the optimal replacement ratio of BCP to SH was 25%–50% (w/w). Accordingly, a sensory evaluation of three PHP samples (PHP0, PHP25, and PHP50) was conducted to compare consumer preferences. PHP0 is a full-SH sample, while PHP25 and PHP50 are samples substituted with each 25% or 50% (w/w) SH.

Table 4 shows the sensory evaluation scores of cooked PHPs. Results showed that there were no significant differences ($p \geq 0.05$) in the scores for all attributes except flavor and hardness. These notable results indicate that consumers do not perceive sensory differences in flavor and hardness despite replacing up to 50% (w/w) of SH with BCP. However, PHP0 exhibited significantly higher ($p < 0.05$) scores than PHP25 and PHP50.

Lipids contribute to food flavor through decomposition into volatile compounds or interactions with secondary products resulting from reactions such as the Maillard reaction, Strecker decomposition during food processing, heating, and cooking (Shahidi & Hossain, 2022). The presence of SH promoted the formation of flavor compounds that positively assisted the taste of PHPs during high-temperature cooking. Consequently, PHP0, which had the highest fat content, showed the highest taste score, followed by PHP50 and PHP25. The taste score of PHP50 was significantly higher ($p < 0.05$) compared to PHP25. These results suggest that consumers may perceive a decrease in the taste of PHPs when SH is replaced with BCP; however, the difference in taste due to SH contents was subtle to detect.

In the tenderness attribute, PHP0 was significantly higher ($p < 0.05$) than the other two samples. These results do not align with the instrumental hardness analysis results conducted with a texture analyzer (Table 3). This observation is due to the instrumental texture analysis, which revealed no significant differences ($p \geq 0.05$) in hardness among the three samples. When PHP0 is put in the mouth and chewed, the SH inside the PHP0 melts due to the temperature of the oral cavity and saliva, creating fluidity and lubrication in the chewed substance (Kupirovič, Elmadfa, Juillerat, & Raspor, 2017). Therefore, the panels would have sensed the PHP0 as a soft texture. Meanwhile, BCP is a cellulose-based material that exhibits increased fluidity when temperatures rise and does not possess melting properties. These characteristics may have contributed to the sensory score for tenderness, resulting in higher scores in the fat-containing sample (PHP0) than the fat-replaced samples (PHP25 and PHP50).

Despite significantly different taste and tenderness ($p < 0.05$) in all samples, their overall preference scores showed no significant difference ($p \geq 0.05$). These findings highlight the potential of BCP to replace up to 50% (w/w) of the existing SH in the PHPs without adversely affecting the overall preference of the PHPs.

Table 4
Sensory evaluation scores of cooked PHPs.

Sensory attributes	PHP0	PHP25	PHP50
Shape	6.72 ± 1.06^{a}	6.20 ± 1.35^{a}	6.20 ± 0.96^{a}
Color	6.16 ± 1.55^{a}	5.68 ± 1.70^{a}	5.40 ± 1.38^{a}
Gloss	5.72 ± 1.24^{a}	5.72 ± 1.54^{a}	5.88 ± 1.13^{a}
Aroma	5.28 ± 1.28^{a}	5.04 ± 1.27^{a}	4.96 ± 1.31^{a}
Flavor	5.44 ± 1.23^{b}	4.44 ± 1.36^{a}	4.68 ± 1.52^{ab}
Oiliness	5.40 ± 1.41^{a}	5.12 ± 0.93^{a}	5.48 ± 0.82^{a}
Tenderness	6.44 ± 1.47^{b}	5.64 ± 0.99^{a}	5.80 ± 1.22^{ab}
Chewiness	5.68 ± 1.28^{a}	5.76 ± 1.51^{a}	6.00 ± 1.00^{a}
Juiciness	5.88 ± 1.56^{a}	5.44 ± 1.23^{a}	5.40 ± 1.38^{a}
Overall preference	5.40 ± 1.53^{a}	4.96 ± 1.21^{a}	5.24 ± 1.51^{a}

Data expressed as mean ± standard deviation of twenty-five replicates ($n = 25$).
9-point hedonic scale: 1 = dislike extremely, 2 = dislike very much, 3 = dislike moderately, 4 = dislike slightly, 5 = neither like nor dislike, 6 = like slightly, 7 = like moderately, 8 = like very much, and 9 = like extremely.
Different lowercase letters (a–b) in the same row indicate a significant difference ($p < 0.05$) among the PHPs determined by Duncan's multiple range test.
PHP: plant-based hamburger patty.

4. Conclusion

This study demonstrates that BCP can be used as a fat substitute by comparing the various characteristics of BCP with conventional fats (CO, MA, SH, BT, BU, and LA). BCP had the most similar appearance and rheological behaviour to fats when its solids content was 3.0% (w/w). In addition, SH was identified as a vegetable fat with characteristics similar to those of 3.0%BCP. Replacement of 25%–50% (w/w) control fat (SH) with BCP in the preparation of PHPs resulted in i) redder, ii) better dimensional stability, iii) lower cooking loss, and iv) higher chewiness of the final products. The sensory evaluation results indicated that PHP25 and PHP50 did not differ significantly ($p < 0.05$) in overall preference scores from PHP0. These results demonstrate that BCP can replace up to 50% (w/w) of SH in PHPs without negatively impacting their overall preference. However, when BCP completely replaced SH at 100% (w/w), a noticeable difference in visual appearance from that of PHP0 in the raw state was observed. Furthermore, no reduction in cooking loss was observed. Therefore, a complete replacement of SH with BCP was considered undesirable. In conclusion, this study presented not only the potential of BCP as a fat replacer in the production of PHPs but also the advantages of this replacement. In particular, it has been proven that BCP can function not only as a fat replacer but also as a stabiliser and binder in PHPs. Moreover, it is anticipated that utilising BCP, as well as PHPs, as fat substitutes in real meat patties will improve their dimensional stability and reduce cooking loss. Further research is required in this area.

CRediT authorship contribution statement

Jung-Soo Lee: Conceptualization, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. **Jaejoon Han:** Conceptualization, Methodology, Resources, Formal analysis, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition.

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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