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ARTICLE

The Replacement Effect of Sucrose with Functional Sugars on Physicochemical Properties of Ground Pork Sausages

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Abstract

The practical use of functional sugars in the food industry has received great attention in reducing calories by replacing sugar and improving technological properties in processed foods. This study evaluated the effects of replacing sucrose with functional sugars (allulose, kestose, and resistant maltodextrin) on the physicochemical properties of ground pork sausages. Pork sausages were prepared by replacing 2% (w/w) sucrose with an equivalent amount of allulose, kestose, or resistant maltodextrin. The uncooked meat batter and cooked sausages were analyzed for pH, instrumental color, viscosity, cooking loss, and textural properties. Replacing sucrose with functional sugars could significantly improve water-holding capacity, as determined by reduced cooking loss, with kestose treatment showing the lowest cooking loss. No significant differences between cooked sausage samples were observed in color characteristics (lightness, redness, yellowness, chroma, and hue angle). However, the replacement significantly reduced the apparent viscosity and textural parameters (except for cohesiveness), particularly in sausages formulated with kestose and resistant maltodextrin. These changes were likely due to the hydration properties of functional sugars and their interactions with muscle proteins. Therefore, this study indicates that functional sugars can offer an effective alternative to sucrose in improving water-holding capacity. Further studies would be warranted to explore sensory attributes and the formulations to guarantee balanced textural properties and desirable consumer acceptance.

Keywords
Allulose, Kestose, Resistant maltodextrin, Texture, Water-holding capacity

Ⅰ. Introduction

Functional sugars are carbohydrates that provide physiological benefits to human health beyond their traditional role as energy sources and sweeteners (Abbasi *et al*., 2021). For instance, various physiological effects of gut health promotion, blood glucose control, and metabolic function support have been found (Clemens *et al*., 2016). Moreover, with the increasing consumer demand for low-calorie or sugar-free processed foods, mainly beverages, snacks, and desserts, the practical use of functional sugars with relatively low-calorie as alternative sweeteners has expanded (Edwards *et al*., 2016). This shift in consumer preferences has led to the use of functional sugars in processed meat products, even those with relatively low added sugar content, to develop healthier products or improve processing properties such as water retention and texture (Hadipernata *et al*., 2016; Hong *et al*., 2020; Yang *et al*., 2024).

In processed meat products, sugars are typically added in 1-2%, but they are crucial in developing desirable flavor, color, texture, and shelf life (Vandendriessche, 2008). Sucrose is one of the most commonly used sugars in processed meat products. It is known to enhance flavor through browning and Maillard reactions and contributes to moisture retention and texture formation due to its hygroscopic properties (Wongwiwat and Wattanachant, 2014). Recently, as consumer concerns about sugar intake grow, functional sugars in processed meats have become more prevalent (Yang *et al*., 2024). In numerous previous studies, the primary aim of incorporating functional sugars, mostly oligo and polysaccharides (e.g., dietary fiber), has been to improve health outcomes and technological properties such as water retention, emulsion stability, and texture modification (Echegaray *et al*., 2023).

In the food industry, functional sugars such as allulose, kestose, and nondigestible dextrin (NDM), as promising candidates for sugar replacers, have gained great attention due to their unique technological properties (Cho *et al*., 2024; Shintani, 2020). $_{\text{D}}$-Allulose is a low-calorie (0.2-0.4 kcal per gram) sugar naturally found in small quantities in fruits, and commercial allulose produced through enzymatic treatment (e.g., kestose 3-epimerase) from $_{\text{D}}$-fructose is extensively used as a sugar replacer in bakery, beverages, dairy products, confectionery products, and sauces (Zhang *et al*., 2016). Moreover, recent studies have reported that allulose could effectively improve the processing characteristics of processed meat products; Hadipernata *et al*. (2016) reported that adding allulose could enhance the elasticity of frozen-stored chicken breast sausages. Hong *et al*. (2020) noted that replacing 3% white sugar with $_{\text{D}}$-allulose could increase the cooking yield of restructured pork patties.

1-Kestose (α-D-glucopyranosyl-(1-2)-β-D-fructofuranosyl-(1-2)-β-D-fructofuranose), called the smallest fructooligosaccharide (FOS), is an emerging functional sugar with unique prebiotic properties (Ni *et al*., 2021). FOS is a mildly sweet, low-calorie, and non-carcinogenic alternative sweetener known to have a gut health-enhancing effect, especially promoting *Bifidobacteria* and *Lactobacillus* spp. (Yun, 1996). Previous studies have shown that FOS containing 1-kestose has a positive impact on the physical and sensory characteristics of processed meat products and has been proposed as a fat substitute based on such quality improvement effect (Cáceres *et al*., 2004; de Sousa *et al*., 2020). However, there has been limited research on the impact of single addition of 1-kestose on improving the quality characteristics of processed meat products.

Resistant maltodextrin, a short-chain glucose polymer, is a dietary fiber obtained from the enzymatically indigestible fraction of soluble dextrin (Li *et al*., 2023). Recently, it has been used as a functional material in various foods to improve intestinal health, weight management, and blood sugar control (Li *et al*., 2023). Previously, resistant maltodextrin could change physical properties by affecting the viscosity and microstructural density of processed meat products and, as a result, improve the sensory characteristics of low-fat meat emulsions (Felisberto *et al*., 2015). Moreover, Cifuentes-Galindres *et al*. (2024) suggested that replacing some meat with resistant maltodextrin could be an effective way to improve the nutritional balance and storage ability of restructured beef steaks.

Given the physiological and technological properties of these functional sugars, it could be expected that adding the functional sugars can improve the multiple quality attributes of processed meat products, mainly water-holding capacity and texture, and contribute to the health-promoting effects. Furthermore, consumers are generally known to prefer sugars that are low in calories and beneficial to health, provided there is no difference in their impact on taste (Jükenbeck *et al*., 2022). Thus, it may be a way to give a positive consumer perception toward processed meat products by replacing sucrose with functional sugars, even in small amounts. However, there have been few studies on the replacement effect of sucrose with functional sugars in processed meat products, and in particular, comparative studies on the impact of various functional sugars have been limited. Therefore, this study evaluated the effect of replacing sugar with allulose, kestose, and resistant maltodextrin in equal amounts on the physicochemical properties of ground pork sausage.

Ⅱ. Materials and Methods

1. Raw materials

Fresh pork ham and back fat (LYD crossbreed) after 48 h postmortem were purchased from a local market. All food additives (salt, sodium nitrite, sodium triphosphate, sugar, and spices, etc.) used in this experiment were purchased of food grade, and allulose (NEXWEET® Allulose 99C, Samyang Corp., Korea), kestose (Samyang Corp., Korea), and resistant maltodextrin (FiberestTM Resistant Dextrin, Samyang Corp., Korea) were kindly provided by Samyang Corporation.

2. Manufacturing procedure of pork sausage

Excessive connective tissue and subcutaneous fat on the surface of the fresh pork ham were removed manually. The trimmed pork ham and back fat were ground using a meat grinder (MN-22S, Hankook Fugee Industries, Korea) with a 6 mm plate. Control pork sausage was prepared as following formula; 60% (w/w) ground pork ham, 20% (w/w) ground backfat, 20% (w/w) ice water, 1.8% (w/w) sodium chloride (NaCl), 0.02% (w/w) sodium nitrite ($NaNO_2$), 0.35% (w/w) sodium tripolyphosphate, 0.55% (w/w) garlic powder, 0.55% (w/w) onion powder, 0.55% (w/w) ginger powder, 0.22% (w/w) black pepper powder, 2.0% (w/w) soy protein isolate, 1.5% (w/w) starch, 0.24% (w/w) monosodium glutamate, and 2.0% (w/w) sucrose. In the functional sugar treatments, the 2.0% (w/w) sucrose was replaced by allulose, kestose, and resistant maltodextrin, respectively, in the same amount. The ground pork back fat, ice water, and other ingredients were manually mixed for 5 min, and the meat batter was filled into a collagen casing (Ø 25 mm, JP-CAN-025-MZ5-00015, Fcase, Poland) using a hand-held stuffer (Sausage stuffer, Korea Times Square Co., Korea). The sausages were heated in a constant temperature water bath (JSIB-22T, JS Research Inc., Korea) set to 75°C until the internal temperature reached 71°C. The internal temperature was monitored using an insert-type digital thermometer (Tes-1384, Tes Electrical Electronic Co., Taiwan). The cooked samples were cooled at room temperature for 1 h, then vacuum-packed in a PE/Nylon bag and stored in a 4°C refrigerator until used for physicochemical analysis.

3. Physicochemical analysis of ground pork sausage

1) pH value

The pH values of raw and cooked pork sausages were determined in triplicate according to the method of Yang *et al.* (2024) with minor modifications. Three grams of sausage samples were homogenized with 27 mL of deionized and distilled water (DDW) using a homogenizer (HG-15A, Daihan Sci., Korea) at 11,000 rpm for 30 s. The pH of the homogenate was read using an electronic pH meter (Orion Star™ A211 pH Benchtop Meter, Thermo Scientific, USA). The pH meter was calibrated with standard buffer solutions (pH 4.01 and 7.0).

2) Instrumental color

The surface color of raw and cooked pork sausage was instrumentally measured using a colorimeter

(Chroma meter, CR 400, Minolta, Japan), and CIE L^* (lightness), a^* (redness), and b^* (yellowness) were recorded from five random spots on the side surface under D_{65} illuminant. The colorimeter was calibrated using the standard white tile (CIE L^*, +93.01; CIE a^*, -0.25; CIE b^*, +3.50). The chroma (saturation index) and hue angle were calculated using the following equations (King *et al*., 2023).

$$\text{Chroma} = (a^{*2} + b^{*2})^{0.5}$$
$$\text{Hue angle} = \tan^{-1}(b^*/a^*)$$

3) Apparent viscosity

The apparent viscosity of meat batter was measured according to the method of Olanwanit and Rojanakorn (2019). Thirty grams of sample was stuffed into a 50 mL centrifuge tube and centrifuged at 100 g for 20 min to remove air bubbles. The viscosity of the sample was read three times using a viscometer (DV3THATJ0, Brookfield Engineering Laboratories Inc., USA) at 10 rpm for 30 s.

4) Cooking loss

The cooking loss of ground pork sausage was calculated by the percentage weight difference between raw and cooked samples using the following equation.

$$\text{Cooking loss (\%)} = [(\text{Weight of raw sample (g)} - \text{Weight of cooked sample (g)}) / \text{Weight of raw sample (g)}] \times 100.$$

5) Texture profile analysis (TPA)

The textural properties of cooked pork sausage were determined using a texture analyzer (CT3, Brookfield Engineering Laboratories Inc., USA). For sample preparation, the cooked sausages were equilibrated to room temperature for 3 h, and cylindrical samples were obtained by cutting the middle portion of each sausage. A twice-compression cycle test (70% compression of the original sample height) was performed with a cylinder probe (diameter of 4 cm). Sample deformation curves were obtained with a 50 kg maximum load cell, and the analysis condition was as follows: pre-test speed 1.0 mm/s, post-test speed 5.0 mm/s, and head speed 2.0 mm/s. The values for hardness (kg), springiness (ratio), cohesiveness, gumminess (kg), and chewiness (kg) were reported (Ham *et al*., 2020).

4. Statistical analysis

The experimental design was a completely randomized block design (n = 3). The obtained data was expressed as mean value and the standard error of the means. One-way ANOVA was performed on the measured variables using the SPSS program (SPSS Inc., USA). Duncan's multiple range test was conducted to compare the significant differences between means ($p<0.05$).

Ⅲ. Result and Discussion

1. pH value

The pH and color characteristics of uncooked meat batter and cooked sausages formulated with functional sugars are shown in Table 1. Replacing sucrose with functional sugars significantly affected the pH of both uncooked meat emulsions and cooked sausages. The pH of the control meat batter was 6.13, while the meat batter with 2% allulose showed a significantly higher pH. However, adding

Table 1. pH value and color characteristics of uncooked meat batter and cooked pork sausage formulated with functional sugars

Trait	Control (2% sucrose)	Treatment			SEM[1]	p value
		2% Allulose	2% Kestose	2% Resistant maltodextrin		
Uncooked meat batter						
pH value	6.13^{b}	6.18^{a}	6.03^{c}	6.01^{d}	0.021	<0.001
CIE L^* (lightness)	62.22	62.08	61.65	63.36	0.378	NS[2]
CIE a^* (redness)	8.92^{a}	8.65^{ab}	7.68^{c}	8.10^{bc}	0.171	0.013
CIE b^* (yellowness)	13.21	13.33	12.55	13.29	0.137	NS
Hue angle	55.97	57.02	58.55	58.62	0.435	NS
Chroma	15.95	15.90	14.72	15.57	0.184	0.033
Cooked sausage						
pH value	6.18^{c}	6.23^{b}	6.26^{a}	6.18^{c}	0.010	<0.001
CIE L^* (lightness)	68.64	68.80	68.94	68.80	0.159	NS
CIE a^* (redness)	8.36	7.72	8.05	8.64	0.139	NS
CIE b^* (yellowness)	10.89	10.25	10.93	10.58	0.117	NS
Hue angle	52.49	53.03	53.65	50.78	0.409	NS
Chroma	13.73	12.83	13.57	13.66	0.154	NS

[1] SEM: standard error of the means.

[2] NS: non-significance (p>0.05).

[a–c] Means sharing the same letters in a row are not significantly different (p>0.05).

2% kestose and 2% resistant maltodextrin resulted in a significantly lower pH compared to the control. After cooking, the pH of treatments tended to increase, with a substantial increase observed in the kestose and resistant maltodextrin

treatments, resulting in a higher pH than that of the control sausages. The pH of 2% (w/w) allulose solution was 5.47, and previous reports on its effect on the pH of meat products have been inconsistent. Hong *et al.* (2020) observed a significant decrease in pH under uncooked and cooked conditions when 3% allulose replaced 3% sugar in chicken breast patties, which contradicts our findings. However, Yang *et al.* (2024) reported no effect on the pH when varying the amount of allulose in sugar-free chicken breast jerky with sorbitol and allulose. Kestose, a type of FOS, is used in the production of commercial fructo-oligosaccharides, and de Sousa *et al.* (2015) reported no effect on the pH of beef patties when FOS containing kestose were added at a 5% level. Recently, Cifuentes-Galindres *et al.* (2024) found that the addition of resistant maltodextrin up to 8% unaffected the initial pH of restructured beef steak. The result of this current study also agrees with the previous observations that adding functional sugars did not affect pH because the difference in pH of cooked pork sausages was slight within 0.1 pH unit.

2. Instrumental color

The replacement of sucrose with functional sugars altered only CIE a^* and chroma of uncooked meat batter ($p<0.05$; Table 1); in particular, 2% kestose treatment resulted in lower redness and chroma of the uncooked meat batter than the control meat batter ($p<0.05$). However, similar values on the color parameters observed in this study, including CIE L^* (lightness), CIE a^* (redness), CIE b^* (yellowness), chroma (saturation index), and hue angle, of cooked pork sausages were found ($p>0.05$), regardless of the replacement of sucrose with functional sugars. In previous studies, no differences in instrumental color parameters were observed for the processed meat products formulated with functional sugars; Hong *et al*. (2020) noted no color differences in raw and cooked chicken patties prepared with 3% sugar and 3% D-allulose. Felisberto *et al*. (2015) also found that FOS and resistant maltodextrin did not impact the instrumental color of reduced-sodium and low-fat emulsion sausages. This result was likely that most sugars are crystalline white powders. Thus, our results also show that replacing 2% sucrose with allulose, kestose, and resistant maltodextrin has no impact on the color characteristics of cooked pork sausages.

3. Apparent viscosity

In general, meat batter and emulsion exhibit the characteristics of shear-thinning, pseudoplastic behavior as one of the non-Newtonian fluids, in which the viscosity decreases with increasing shear rate (Genccelep *et al*., 2015). The viscosity of meat batter is related to water-holding capacity, fat-binding capacity, protein solubility, and emulsion stability, which in turn is one of the fundamental factors affecting texture and sensorial mouthfeel (Sarteshnizi *et al*., 2015). The apparent viscosity of meat emulsions formulated with allulose, kestose, and resistant maltodextrin is shown in Fig. 1. The addition of functional sugar evidently changed the maximum viscosity of uncooked meat batter ($p<0.05$). The kestose and resistant maltodextrin treatments showed a significantly lower maximum viscosity than the control meat batter. Thus, our result indicates that replacing 2% sucrose with functional sugar, particularly kestose and resistant maltodextrin, might make the meat batter less viscous and dense. Similar to our observations, Hadipernata *et al*. (2016) found that replacing 2.5%

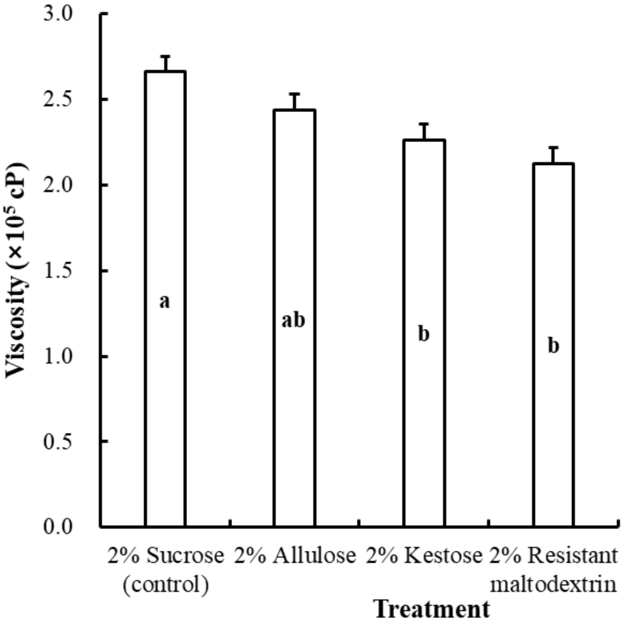

Fig. 1. Apparent viscosity of meat batters formulated with functional sugars. Error bar indicates the standard error of the means. a,b Means sharing the same letters are not significantly different ($p>0.05$).

(w/w) sucrose with allulose could decrease the viscosity of chicken breast sausage and suggested that the reduced viscosity might be associated with the improved water-holding capacity. Moreover, Felisberto *et al.* (2015) reported that FOS and resistant maltodextrin had no improvement effects of the shear storage modulus (*G*`) of reduced-sodium and low-fat meat emulsion. These previous findings help us understand the decreased viscosity in the functional sugar treatments in this study, and this phenomenon was probably due to the hydrated functional sugars influencing protein-protein or protein-water interactions.

4. Cooking loss

The replacement effect of sucrose with functional sugars on the cooking loss of ground pork sausages is shown in Fig. 2. When compared to control sausage (2.0%), significantly lower cooking losses of functional sugar treatments were found, in order of allulose (1.5%), resistant maltodextrin (1.4%), and kestose (1.1%). Thus, this result shows that replacing 2% sucrose with functional sugars such as allulose, kestose, and resistant maltodextrin could improve the water-holding capacity of ground pork sausages. Many previous studies have similarly found that functional sugars could improve water-holding capacity determined by cooking loss or yield; Hong *et al.* (2020) observed that replacing 3% sugar with $_{\mathrm{D}}$-allulose increases the cooking yield of chicken breast patties. Hadipernata *et al.* (2016) observed decreased expressible water in chicken breast sausage when $_{\mathrm{D}}$-allulose replaced 2.5% sucrose. Sugar groups can generally be hydrated and solubilized in water, forming hydrogen bonds between water molecules and hydroxyl groups in sugar molecules (Tas *et al.*, 2022). Although the maltodextrin equivalent value of resistant maltodextrin used in this study was not measured, kestose may have the most hydroxyl groups (e.g., sucrose, 8 hydroxyls; allulose, 5 hydroxyls; kestose, 12 hydroxyls). As a result, kestose can form more hydrogen bonds with water molecules, which might be one of the possible reasons for understanding the lowest cooking loss in kestose treatment in this study.

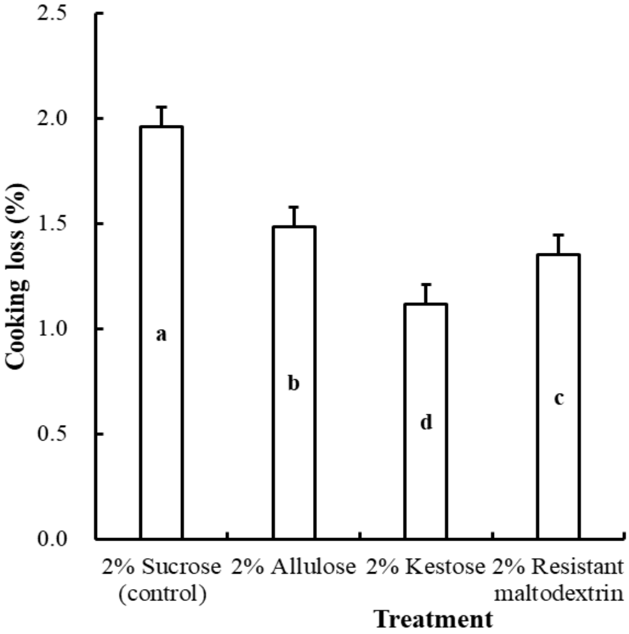

Fig. 2. Cooking loss of cooked pork sausages formulated with functional sugars. Error bar indicates the standard error of the means. a-d Means sharing the same letters are not significantly different (p>0.05).

5. Textural properties

The replacement effect of sucrose with functional sugars on the textural properties of cooked pork sausages is shown in Table 2. Except for cohesiveness, the textural parameters of cooked sausages, such as hardness, springiness, chewiness, and gumminess, were significantly changed when the 2% sucrose was replaced by the functional sugars ($p<0.05$). In particular, resistant maltodextrin treatment showed the lowest hardness, springiness, gumminess, and chewiness. Sugars generally have hygroscopic properties that absorb or bind water from the surroundings. In this regard, Yang *et al.* (2024) reported that an increase in the added amount of allulose could reduce the shear force of chicken jerky, resulting in tender texture, which is also in agreement with our observation showing the decreased cooking loss in Fig. 2. Moreover, functional sugars could be understood to affect the physical bond between meat particles or chemical bond between molecules in processed meat products. Crehan *et al.* (2000) reported that the interruption of maltodextrin between meat particles could decrease the gumminess of frankfurters. According to Felisberto *et al.* (2015), the addition of FOS and resistant maltodextrin on the reduced-sodium low-fat meat emulsion increased the gelation temperature and explained that this phenomenon might allow insufficient thermal denaturation and aggregation of myosin molecules, which could be related to the formation of less elastic and firm texture of the meat emulsion (Felisberto *et al.*, 2015). However, the impact of insufficient thermal denaturation of muscle proteins on protein-water interactions in meat batter remains inconclusive, as denatured muscle proteins typically lose their ability to bind water molecules (Huff-Lonergan and Lonergan, 2005). Taken together, the decreased texture parameters in the functional sugar treatment, especially resistant maltodextrin treatment, might be associated with (1) improved water-holding capacity, (2) weak binding between meat particles, and (3) insufficient gelation with increased gelation temperature.

Ⅳ. Conclusion

This study investigated the replacement effects of 2% (w/w) sucrose with allulose, kestose, and resistant maltodextrin on the physicochemical properties of ground pork sausages. The findings revealed that allulose, kestose, and resistant maltodextrin could improve water-holding capacity as determined by reduced cooking loss. While the sucrose replacement had minimal impact on pH and color

Table 2. Textural properties of cooked pork sausage formulated with functional sugars

Trait	Control (2% sucrose)	Treatment			SEM[1]	p value
		2% Allulose	2% Kestose	2% Resistant maltodextrin		
Hardness (kg)	6.15^{a}	5.76^{a}	5.70^{a}	5.09^{b}	0.135	0.015
Springiness (ratio)	0.64^{a}	0.66^{a}	0.62^{a}	0.52^{b}	0.017	0.004
Cohesiveness	0.18	0.17	0.18	0.17	0.002	NS[2]
Gumminess (kg)	1.08^{a}	0.98^{ab}	0.99^{ab}	0.85^{b}	0.031	0.043
Chewiness (kg)	0.69^{a}	0.65^{a}	0.62^{a}	0.45^{b}	0.030	0.001

[1] SEM: standard error of the means.

[2] NS: non-significance ($p>0.05$).

^{a,b} Means sharing the same letters in a row are not significantly different ($p>0.05$).

characteristics, it altered the apparent viscosity and textural properties, except for cohesiveness. In particular, sausages with kestose and resistant maltodextrin exhibited reduced viscosity and less firm textures, likely due to their hydration properties and interactions with muscle proteins. Our findings indicate the potential of functional sugars to enhance the water-holding capacity of processed meat products, which is relevant for the meat processing industry by offering innovative development concepts for healthier meat products and potentially fostering positive consumer perceptions. However, because sensory palatability may decline due to the less firm and elastic texture, it may be necessary to study the use of mixtures with dietary fibers that have thickening effects. In addition, although the effects of functional sugars were evaluated at the same quantitative levels in this study, careful consideration of the addition levels will be necessary in sensory evaluations due to differences in sweetness intensity. Taken together, further research should explore the impact of functional sugars at different addition levels on the eating quality attributes of processed meat products to ensure consumer acceptance.

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Ⅵ. Conflicts of Interest

Si-Young Kim, Hyun-Shik Choi, and Jung-Sook Han were employed by the company Samyang Corp.. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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