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Functional Cookies With Black Garlic and Jackfruit Seed Powder: Impact on Textural Properties, Antioxidant Activity, and Reduced Starch Hydrolysis Index

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ABSTRACT

This study developed cookies containing black garlic powder and jackfruit seed powder to improve nutritional and functional properties while maintaining sensory quality and reducing in vitro starch hydrolysis. A two-phase formulation strategy was used. In Phase I, black garlic powder replaced wheat flour at 0–30%, and 15% was selected based on color, physical properties, texture, and sensory acceptance. In Phase II, jackfruit seed powder was incorporated at 0–30% into the 15% black-garlic formulation. Increasing black garlic powder increased cookie spread and reduced cookie thickness. The optimized cookie containing 15% black garlic powder and 15% jackfruit seed powder had 8.23% protein, 6.33% total dietary fiber, and 231 mg gallic acid equivalents (GAE)/100 g. Radical-scavenging activity after baking was 67.78 ± 0.23%, while the starch hydrolysis index was 46.45 ± 0.51% relative to white bread. The combined formulation therefore provided a cookie with favorable sensory, textural, nutritional, and antioxidant characteristics and lower in vitro starch hydrolysis. The findings support the valorization of black garlic and jackfruit seed resources in value-added cookie development.

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1. Introduction

Food science increasingly views cookies as carriers of functional ingredients. Consumers seek products that retain sensory quality while addressing concerns such as glycemic response and micronutrient intake [1]–[3]. However, replacing wheat flour with functional ingredients can weaken gluten structure and compromise cookie crispness and texture. Black garlic and jackfruit seeds are promising resources for addressing these needs.

Black garlic is produced from fresh garlic through thermal-humid processing, resulting in the accumulation of bioactive compounds, including S-allyl cysteine (SAC), polyphenols, and melanoidins. These compounds are associated with antioxidant activity and other potential health benefits. However, the high reducing-sugar content and hygroscopicity of black garlic powder (BGP) may adversely affect dough handling and cookie texture, potentially resulting in softer and more fragile products [4]–[6]. Therefore, identifying complementary ingredients that can improve formulation performance while maintaining acceptable sensory properties is an important consideration in developing black garlic-enriched cookies.

Jackfruit seeds are an underutilized agricultural by-product containing substantial amounts of starch and protein. Previous research has suggested that hydrothermal processing followed by cooling can promote starch retrogradation and potentially contribute to the formation of type III resistant starch (RS3), which is associated with dietary fiber functionality and reduced starch digestibility [7]. However, the extent of RS3 formation depends on processing conditions and requires direct verification. Given their starch content and potential contribution to cookie texture and nutritional composition, jackfruit seed powder (JSP) represents a promising ingredient for combination with BGP. Accordingly, this study first evaluated different BGP substitution levels to select a suitable base formulation and then

incorporated JSP at different levels into the selected formulation. The combined effects were assessed through dough texture, cookie geometry and color, sensory acceptance, nutritional composition, post-baking DPPH radical-scavenging activity, and in vitro starch hydrolysis. This approach provides formulation-specific evidence of the effects of combining BGP and JSP without presuming RS3 formation, antioxidant retention during baking, or physiological benefits in humans.

Although black garlic and jackfruit seeds have individually been studied in food products, their combined use in a single cookie matrix remains insufficiently explored. We hypothesized that combining the antioxidant capacity and sensory characteristics of BGP with the starch- and fiber-rich properties of JSP would improve structural quality and functional value. The objective was therefore to determine suitable BGP and JSP substitution levels and develop a cookie with desirable texture, flavor, nutritional value, and low starch hydrolysis.

2. Materials and Methods

Black garlic bulbs were procured from Ladago Production and Trading Co., Ltd. (Vietnam). The cloves were peeled, sliced to 1–2 mm, dried at 55 °C for 72 h, equilibrated in a desiccator, mixed with 1% (w/w) silicon dioxide (E551) to prevent agglomeration, ground, sieved through a 100-mesh sieve, and stored in moisture-barrier pouches at 0–4°C.

Jackfruit seeds were obtained from Minh Phat Co., Ltd. (Vietnam), thoroughly washed to remove impurities, and dried at 40°C for 48 h to facilitate the removal of the outer white skin. The peeled seeds were subsequently steamed at 100°C for 30 min to soften the seed matrix and potentially reduce certain heat-sensitive anti-nutritional factors. After cooling to ambient temperature, the seeds were coarsely ground and stored at 0–4°C for 48 h. This cold-storage step may have promoted starch retrogradation, involving the reassociation of starch chains, particularly amylose, following heat treatment. Such structural reorganization can potentially contribute to the formation of type RS3. However, RS3 formation and its extent were not directly confirmed in the present study. Finally, the treated material was dried in a convection oven at 60°C for 7 h until its moisture content was below 10%, milled into a fine powder, and passed through a 100-mesh sieve to obtain a relatively uniform particle size. The resulting jackfruit seed powder was packaged in moisture-barrier aluminum pouches and stored at 4°C until further use.

Commercial low-protein wheat flour (8–9% protein; Bakers' Choice No. 8, Interflour Vietnam), shortening, whole milk (TH True Milk), isomalt, lecithin, sodium bicarbonate, ammonium bicarbonate, and other food-grade ingredients were used. Black garlic powder and jackfruit seed powder were incorporated by replacing wheat flour at the specified substitution levels. A commercial cookie was used for nutritional and functional comparison.

2.1. Preparation of experimental cookie formulations

The study was designed to evaluate the impact of BGP substitution based on a fixed total flour weight of 30 g per treatment. BGP was used to replace wheat flour at substitution levels of 0, 5, 10, 15, 20, 25, and 30% (w/w), based on the original wheat flour weight of 30 g per batch. Accordingly, the BGP content ranged from 0 to 9 g, while the wheat flour content decreased from 30 to 21 g. The quantities of all other ingredients were kept constant across formulations: 12 g shortening, 9 g isomalt, 7.5 g milk, 7.5 g whole eggs, 0.65 g baking powder, 0.4 g salt, 0.24 g lecithin, 0.2 g xanthan gum, and 1 g vanilla extract.

Black garlic–jackfruit cookies (BJC): The product optimization phase involved incorporating JSP into the previously selected black garlic cookie formulation. The total flour weight was maintained at 30 g per treatment, with BGP fixed at 15% (4.5 g) of the original total flour weight. JSP replaced the remaining wheat flour fraction (25.5 g) at substitution levels of 0, 5, 10, 15, 20, 25, and 30% (w/w), corresponding to JSP quantities of 0, 1.275, 2.55, 3.825, 5.10, 6.375, and 7.65 g, respectively. The wheat flour quantity was reduced accordingly to maintain a constant total flour weight of 30 g, including BGP and JSP. All other ingredients, including shortening, isomalt, whole eggs, milk, and additives, were kept constant across formulations to ensure comparability among treatments.

2.2. Measurement of cookie hardness

Cookie hardness was measured using a CT3 Texture Analyzer (Ametek Brookfield) with a three-point bend fixture (TA-TPB). The instrument was configured with the following operating parameters: compression test mode, a target deformation distance of 10.0 mm, a trigger load of 5.0 g, and a test speed of 1.0 mm/s. Cookie hardness was defined as the maximum breaking force recorded at the moment of complete structural rupture [8].

2.3. Determination of cookie diameter, thickness, and spread ratio

Cookie diameter (D) and thickness (T) were measured with a Vernier caliper following the reported method. Diameter was measured across the cookie, thickness at its center, and spread ratio (SR) was calculated as D/T, as shown in Equation (1).

$$SR = \frac{D}{T} \quad (1)$$

2.4. Texture Profile Analysis (TPA) of Dough

Dough texture was determined using a two-cycle compression Texture Profile Analysis (TPA) method on a Brookfield CT3 Texture Analyzer equipped with a TA-AACC36 probe and a TA-RT-KIT fixture. Cylindrical dough samples (20 mm in diameter and 20 mm in height) were placed at the center of the fixture and subjected to two consecutive compression cycles to 50% deformation with a trigger load of 5 g and both test and return speeds set at 1.5 mm/s; the probe was wiped clean after each measurement. Texture parameters, including hardness, cohesiveness, springiness, gumminess, and adhesiveness, were obtained directly from the instrument software**.** All measurements were performed in six replicates, and the mean values were calculated.

2.5. Determination of water absorption capacity (WAC)

WAC of black garlic powder, jackfruit seed powder, and wheat flour was determined by a centrifugation method with minor modifications. A known mass of flour was hydrated, mixed, centrifuged, and the retained water was determined gravimetrically. WAC was expressed as g water/g sample [9], [10]. Briefly, 1.0 g of the sample was accurately weighed into a pre-weighed centrifuge tube and dispersed in 10 mL of distilled water. The suspension was vigorously vortexed for 2 minutes to ensure thorough hydration and subsequently allowed to stand at room temperature for 30 minutes. Following incubation, the mixture was centrifuged at 3000 $\times g$ for 20 minutes. The supernatant was carefully decanted, and the tube containing the wet sediment was inverted at a 45° for 10 minutes to drain excess liquid before re-weighing. WAC was calculated as the difference in weight between the wet sediment and the initial dry sample, expressed as grams of water absorbed per gram of the sample (g/g).

2.6. Determination of cookie color

Cookie surface color was measured with a Minolta CR-400 chromameter. L*, a*, and b* values were recorded, and total color difference (ΔE) was calculated relative to the control using the standard CIELab relationship, as shown in Equation (2).

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

where ΔL = L*sample − L*control, Δa = a*sample − a*control, and Δb = b*sample − b*control.

2.7. Determination of total polyphenol content of cookies

Total polyphenol content (TPC) was determined by extracting 1.0 g of ground sample twice with 80% methanol (1:25 w/v) under dark conditions, followed by centrifugation at 6000 × g for 15 min. The pooled supernatants were diluted 50-fold with 80% methanol. For the colorimetric assay, 200 µL of the diluted extract was mixed with 1.4 mL of double-distilled water and 100 µL of Folin-Ciocalteu reagent. After an 8-minute incubation in the dark at room temperature, 300 µL of 20% (w/v) Na_2CO_3 was added.

The mixture was incubated for an additional 2 h in the dark before measuring the absorbance at 765 nm. TPC was quantified using a gallic acid standard curve (10–50 ppm, $R^2 > 0.99$) and expressed as mg GAE/100 g dry weight [11].

A gallic acid calibration curve (10–50 ppm; $R^2 > 0.99$) was used for quantification. TPC was expressed as mg GAE/100 g sample.

$$TPC\ (mg\ GAE/100\ g) = \frac{C \times V \times d}{m} \times 100/1000 \quad (3)$$

where C represents the gallic acid concentration derived from the calibration curve (µg/mL), V is the total recovered extract volume (mL), d is the dilution factor, and m is the sample mass (g). The factor 100/1000 converts the result to mg GAE/100 g.

2.8. Determination of antioxidant activity of cookies

The antioxidant activity of the samples was determined using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay, based on the principle that the reduction of the purple DPPH radical to a stable yellow hydrazine by antioxidant compounds results in a measurable decrease in absorbance at 517 nm. The experimental procedure was adapted from the previously reported protocol with specific modifications introduced to optimize compatibility with the food matrix [12], [13].

Extraction Protocol: Precisely 1.0 g of the finely ground sample was weighed and dispersed in 16 mL of 80% methanol. The mixture was thoroughly agitated and incubated in the dark for 24 hours to facilitate the extraction of bioactive compounds. Subsequently, the mixture was filtered through Whatman No. 1 filter paper to collect the supernatant, which was then stored at -20 ºC pending further analysis.

Colorimetric Reaction: An aliquot of 0.2 mL of the sample extract was transferred into a test tube containing 3.8 mL of 0.1 mM DPPH solution. The resulting mixture was thoroughly agitated for 3 minutes and subsequently incubated in the dark at room temperature for 30 minutes to facilitate the reaction. The absorbance of the sample (ABS_{sample}) was measured at 517 nm using a spectrophotometer. A control sample ($ABS_{control}$) was prepared under identical conditions, substituting the sample extract with the extraction solvent (80% methanol) [14].

RSA was calculated according to Equation (4).

$$RSA\ (\%) = (1 - ABS_{sample}/ABS_{control}) \times 100 \quad (4)$$

where ABS_{sample} is the absorbance of the reaction mixture containing sample extract and DPPH, and $ABS_{control}$ is the absorbance of the control solution containing 80% methanol and DPPH. It should be noted that intrinsic pigments from black garlic (such as melanoidins) and jackfruit seed phenolics can exhibit minor background absorbance at 517 nm; therefore, calculating scavenging activity without an individualized sample-color blank represents a conservative underestimation of the actual radical scavenging capacity, as background pigment absorbance slightly inflates ABS_{sample}.

2.9. Determination of the in vitro starch hydrolysis index (SHI) of cookies

The *in vitro* SHI was determined according to the protocol of Goñi et al. [15], with minor modifications. The enzymatic solution was prepared by dissolving 0.1 mL of α-amylase (AHA-400, Angek Yeast Co., China, 260 U/g) in 100 mL of phosphate buffer (pH 6.9, containing 0.02% NaN_3) and equilibrated at 37°C. Dried, finely milled cookie samples (0.5 g) were dispersed in 25 mL of the buffer and agitated at 37°C for 10 minutes prior to the initiation of hydrolysis via the addition of 5.0 mL of the enzyme solution. A 250 µL aliquot of the sample was collected at 0 (immediately after enzyme addition), 20, 60, 90, 120, 180, 210, 240, 270, 300, 330, 360, 390, 420, 450, and 480 min. Each aliquot was transferred to a test tube, and 250 µL of DNS reagent (containing 1 g of DNS, 30 g of sodium potassium tartrate, and 1.6 g of NaOH) was added. After cooling to ambient temperature, the absorbance was measured at 530 nm to quantify reducing sugars. The degree of hydrolysis (DH) was calculated using a glucose standard curve and fitted to the non-linear regression model described by Goñi et al. [15]:

$$C = C_{\infty} \times (1 - e^{-kt}) \quad (5)$$

where C is the concentration at time t, C_{∞} is the equilibrium concentration, and k is the kinetic constant. The area under the hydrolysis curve (AUC) was computed using Origin 8.5.1 software, and the SHI was subsequently derived as the percentage ratio of the sample AUC to that of white bread (reference standard, SHI = 100).

2.10. Determination of the nutritional composition of cookies

Nutritional composition (energy, carbohydrate, lipid, protein, dietary fiber, total polyphenols, and moisture) was determined according to standard food-analysis procedures [16].

2.11. Sensory evaluation of cookies

Sensory acceptance was evaluated by 75 untrained consumers using a 9-point hedonic scale [17]. Panelists were recruited based on specific inclusion criteria, which required stable health, regular consumption of cookies, and the absence of known allergies to the product's ingredients. Participants evaluated the samples for key attributes including color, aroma, taste, texture, and overall acceptability. The sensory evaluation was quantified using a 9-point hedonic scale, where higher numerical values corresponded to a greater level of consumer preference.

2.12. Statistical analysis

All experiments were conducted using three independent batches for each formulation. Data are expressed as mean ± standard deviation (SD). Statistical differences among formulations were evaluated using one-way analysis of variance (ANOVA), followed by Tukey's honestly significant difference (HSD) test, using SPSS version 16.0. Differences were considered statistically significant at $p < 0.05$.

3. Results and Discussion

3.1. Effect of black garlic powder (BGP) substitution on cookie color

Table 1. *Color characteristics of cookies with different black garlic powder levels.*

BGP(%)	L^*	a^*	b^*	ΔE	Note
0	74.41 ± 0.06^{a}	5.56 ± 0.12^{e}	31.62 ± 0.05^{a}	-	*BGP: Black garlic powder; L^*, a^*, b^* are CIELab color coordinates representing lightness, redness/greenness, and yellowness/blueness, respectively; ΔE is total color difference compared to the control sample.* *Values are expressed as mean ± standard deviation (n=3). Different superscript lowercase letters (a–g) within the same column indicate statistically significant differences ($p < 0.05$)*
5	59.74 ± 0.13^{b}	8.44 ± 0.09^{d}	30.08 ± 0.11^{b}	15.03 ± 0.15^{g}	
10	53.83 ± 0.21^{c}	8.86 ± 0.19^{c}	24.57 ± 0.13^{c}	21.99 ± 0.17^{f}	
15	45.63 ± 0.23^{d}	9.64 ± 0.21^{b}	22.82 ± 0.08^{d}	30.36 ± 0.20^{e}	
20	43.69 ± 0.16^{e}	9.79 ± 0.05^{b}	20.75 ± 0.06^{e}	32.85 ± 0.16^{d}	
25	40.83 ± 0.20^{f}	9.80 ± 0.07^{b}	19.64 ± 0.10^{f}	35.89 ± 0.19^{c}	
30	35.20 ± 0.14^{g}	10.55 ± 0.04^{a}	16.73 ± 0.12^{g}	42.23 ± 0.10^{a}	

As shown in Table 1, BGP significantly affected cookie color ($p < 0.05$). L* decreased from 74.41 in the control to 35.20 at 30% BGP, while a* increased from 5.56 to 10.55 and b* decreased from 31.62 to 16.73. Consequently, ΔE increased to 42.23 at 30%, indicating a marked color difference from the control. The progressive darkening resulted from the intrinsic pigments of black garlic and intensified Maillard and caramelization reactions during baking at 160 °C. BGP supplies reducing sugars and free amino acids generated during fermentation, which promote melanoidin formation during heating. Moderate substitution (5–15%) produced a preferred golden-brown color, whereas 20–30% produced excessive darkening and a burnt appearance [4], [18], [19].

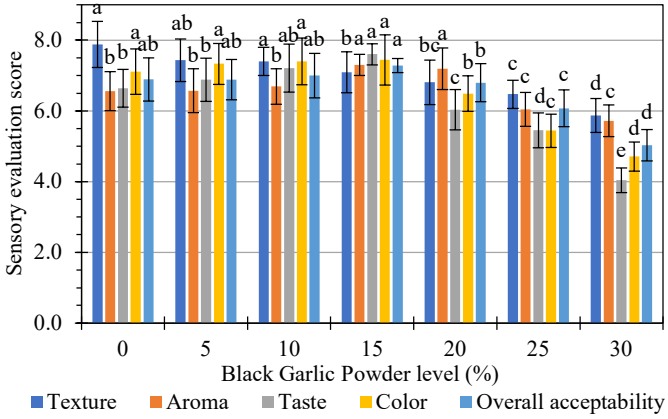
3.2. Effect of black garlic powder on the physical properties of cookies

Table 2. *Physical properties of black garlic cookies with different black garlic powder levels.*

BGP (%)	*D* (mm)	*T* (mm)	*SR*	*Note*
0	43.92±0.06^{f}	8.53±0.06^{a}	5.15±0.03^{g}	*BGP: Black garlic powder substitution;* *D: Diameter;* *T: Thickness;* *SR: Spread ratio.* *Data are presented as mean ± standard deviation (n=3), where different superscript lowercase letters (a–g) within the same column indicate statistically significant differences ($p < 0.05$).*
5	44.08±0.03^{e}	8.08±0.03^{b}	5.46±0.02^{f}	
10	44.91±0.04^{d}	7.98±0.04^{c}	5.63±0.03^{e}	
15	45.13±0.05^{c}	7.41±0.03^{d}	6.09±0.02^{d}	
20	45.18±0.04^{c}	6.97±0.05^{e}	6.48±0.05^{c}	
25	45.95±0.05^{b}	6.41±0.03^{f}	7.17±0.04^{b}	
30	46.12±0.04^{a}	5.56±0.04^{g}	8.30±0.05^{a}	

Increasing BGP changed cookie geometry: diameter increased, thickness decreased, and spread ratio increased (Table 2). These changes indicate greater dough flow and reduced structural development as BGP replaced gluten-containing wheat flour. BGP had lower WAC (~0.55 g/g) than wheat flour (~0.73 g/g), increasing free water and reducing dough viscosity. Its reducing sugars and soluble fibers may also have acted as plasticizers, further increasing dough mobility during baking [20], [21]. Conversely, the marked reduction in thickness (*T*) serves as direct evidence of the "gluten dilution" phenomenon. Gluten functions as the viscoelastic backbone/scaffold responsible for gas retention and maintaining the leavened structure. The replacement of wheat flour with gluten-free BGP weakened this protein network. This compromised framework was unable to retain the gas generated by the leavening agents and steam, causing the cookie to collapse and fail to develop vertical height [22]. At 25–30% BGP, excessive spreading and low thickness indicated a weak, fragile matrix. Thus, although a higher spread ratio can be desirable for some cookies, the observed structural weakening supported the need for reinforcement with JSP [23].

3.3. Effect of black garlic powder on sensory evaluation



Note: Values are means ± SD. Different lowercase letters (a, b, c, etc.) denote significant differences within each sensory attribute based on ANOVA and Tukey's test ($p < 0.05$).

Figure 1. *Sensory evaluation scores of BGC with different black garlic powder levels.*

Figure 1 shows that BGP significantly affected the sensory attributes of the cookies ($p < 0.05$). Overall acceptability increased with BGP substitution, reaching the highest score at 15% (7.28 ± 0.69), before declining at higher substitution levels. The overall acceptability score at 15% was significantly higher than that at 20% (6.80 ± 1.24; $p < 0.05$), but did not differ significantly from that at 10% (7.00 ± 0.61; $p > 0.05$). Texture scores decreased from 7.88 in the control to 5.87 at 30% BGP, suggesting that excessive substitution may negatively affect the characteristic texture of the cookies. The 15% BGP formulation received the highest aroma (7.31 ± 0.75) and taste (7.60 ± 0.97) scores. At higher

substitution levels, taste acceptance declined markedly, reaching 4.04 at 30% BGP, possibly because excessive formation of Maillard reaction and caramelization products contributed to bitter or burnt notes [23], [24]. The 15% formulation also achieved the highest color preference score (7.44 ± 0.81), whereas the score decreased to 4.71 ± 1.39 at 30% BGP, potentially reflecting reduced acceptance of the darker appearance. Although the texture score at 15% BGP (7.09 ± 0.87) was slightly lower than that of the 10% formulation (7.40 ± 0.99), the 15% formulation exhibited the most favorable overall sensory profile, particularly in aroma and taste. Therefore, 15% BGP was selected as the preferred base formulation for subsequent incorporation of JSP.

3.4. Effect of jackfruit seed powder on the textural properties of black garlic cookie dough

Table 3. *Moisture content and textural properties of black garlic–jackfruit cookie dough with different jackfruit seed powder levels.*

JSP (%)	*MC* (%)	*H* (g)	*S*	*Co*	*G* (g)	*A* (g·s)
0	31.87 ± 0.05^{a}	137.67 ± 26.31^{e}	0.338 ± 0.040^{a}	0.236 ± 0.008^{a}	32.31 ± 5.05^{d}	65.55 ± 2.90^{a}
5	31.32 ± 0.15^{b}	177.33 ± 10.30^{de}	0.298 ± 0.020^{b}	0.233 ± 0.012^{ab}	41.45 ± 4.38^{c}	53.08 ± 2.42^{b}
10	30.61 ± 0.18^{c}	191.67 ± 14.37^{cd}	0.287 ± 0.015^{b}	0.228 ± 0.008^{ab}	43.71 ± 2.57^{bc}	49.07 ± 0.66^{c}
15	30.08 ± 0.05^{d}	213.17 ± 9.29^{bcd}	0.276 ± 0.005^{b}	0.220 ± 0.007^{bc}	46.87 ± 1.84^{bc}	44.25 ± 1.37^{d}
20	29.84 ± 0.04^{e}	237.00 ± 12.56^{bc}	0.260 ± 0.012^{bc}	0.211 ± 0.007^{c}	50.08 ± 3.01^{b}	43.46 ± 0.89^{d}
25	28.22 ± 0.15^{f}	243.17 ± 13.25^{b}	0.258 ± 0.020^{bc}	0.208 ± 0.003^{c}	50.52 ± 3.48^{b}	40.33 ± 0.64^{e}
30	27.42 ± 0.17^{g}	329.83 ± 53.8^{a}	0.223 ± 0.012^{c}	0.186 ± 0.011^{d}	60.98 ± 6.41^{a}	38.93 ± 0.71^{e}

Note: MC: Moisture content; H: Hardness; S: Springiness (dimensionless); Co: Cohesiveness (dimensionless); G: Gumminess; A: Adhesiveness. Data are presented as mean ± standard deviation (n=3). Different superscript lowercase letters (a–g) within the same column indicate statistically significant differences ($p < 0.05$).

As shown in Table 3, the 0% JSP formulation in Phase II nominally corresponds to the selected 15% BGP formulation established in Phase I and serves as the internal reference benchmark for evaluating the effects of JSP incorporation. Because Phase I and Phase II were executed as two sequential, self-contained experimental phases over distinct operational timelines, minor inter-batch variations in dough handling and environmental equilibration inevitably occurred. Accordingly, Phase I and Phase II were treated as independent experimental blocks, with statistical evaluations and percentage-dependent trends interpreted strictly within each respective formulation series. Table 3 shows that JSP altered dough moisture and texture profile analysis parameters, indicating changes in dough mechanical behavior [25], [26]. Dough moisture decreased from 31.87% to 27.42% as JSP incorporation increased from 0 to 30%. This trend may be associated with the lower moisture content and higher WAC of JSP (2.49 g/g) compared with BGP (0.55 g/g) and wheat flour (0.73 g/g) [26]. Meanwhile, dough hardness increased from 137.67 to 329.83 g, whereas springiness and cohesiveness decreased, and adhesiveness declined from 65.55 to 38.93 g·s. The increase in hardness indicates that JSP incorporation produced a firmer dough, while the reduction in adhesiveness may indicate less sticky and potentially easier-to-handle dough. However, increased hardness alone does not demonstrate improved technological quality. The practical benefits of these textural changes must be considered alongside the resulting cookie properties and sensory acceptance.

3.5. Effect of Jackfruit Seed Powder Substitution on Cookie Color

According to Table 4**,** the 0% JSP formulation in Phase II serves as the internal reference benchmark ($L^* = 36.02 \pm 0.11$) for the subsequent matrix-optimization series. Although nominally identical in raw composition to the 15% BGP formulation from Phase I, the lower baseline lightness reflects the extreme sensitivity of black garlic reducing sugars to inter-batch thermal browning kinetics and surface moisture reflectance across distinct operational timelines. Therefore, color parameters and ΔE values were evaluated strictly within their independent experimental framework. Color was assessed on the baked

cookies because final color reflects both ingredient pigmentation and heat-induced reactions. With 15% BGP fixed, increasing JSP reduced L* from 36.02 to 30.30 and b* from 21.38 to 15.47, while a* increased from 11.58 to 12.74. ΔE reached 8.30 at 30% JSP ($p < 0.05$), confirming progressive darkening. During baking at 160 °C, reducing sugars and free amino acids associated with JSP and BGP promoted Maillard browning. Thus, the final cookie was substantially darker than predicted from the raw ingredient mixture alone [23], [27].

Table 4. *Color characteristics of black garlic–jackfruit cookies with different jackfruit seed powder levels.*

JSP (%)	L^*	a^*	b^*	ΔE
0	36.02 ± 0.11^{a}	11.58 ± 0.06^{f}	21.38 ± 0.12^{a}	-
5	35.51 ± 0.49^{b}	11.71 ± 0.08^{e}	20.19 ± 0.18^{b}	1.31 ± 0.26^{f}
10	33.68 ± 0.22^{c}	11.89 ± 0.05^{d}	18.40 ± 0.03^{c}	3.79 ± 0.13^{e}
15	32.92 ± 0.02^{d}	12.10 ± 0.11^{c}	18.11 ± 0.07^{d}	4.53 ± 0.04^{d}
20	31.52 ± 0.43^{e}	12.13 ± 0.06^{c}	16.40 ± 0.20^{e}	6.72 ± 0.43^{c}
25	30.92 ± 0.11^{f}	12.36 ± 0.09^{b}	15.97 ± 0.10^{f}	7.47 ± 0.09^{b}
30	30.30 ± 0.31^{g}	12.74 ± 0.08^{a}	15.47 ± 0.16^{g}	8.30 ± 0.27^{a}

Polyphenols and flavonoids from jackfruit seeds may also contribute to thermal browning through oxidation and polymerization. Together, these reactions explain the dark-brown color of the baked composite cookies [26], [28]. The 5–15% JSP samples retained acceptable warm-brown tones, with the highest color preference at 15%. At 25–30%, L* fell below 31 and ΔE exceeded 7, producing an excessively dark, burnt-like appearance and limiting sensory acceptance.

3.6. Effect of Jackfruit Seed Powder Substitution on the Physical Properties of Cookies

Table 5. *Physical properties of black garlic–jackfruit cookies with different jackfruit seed powder levels.*

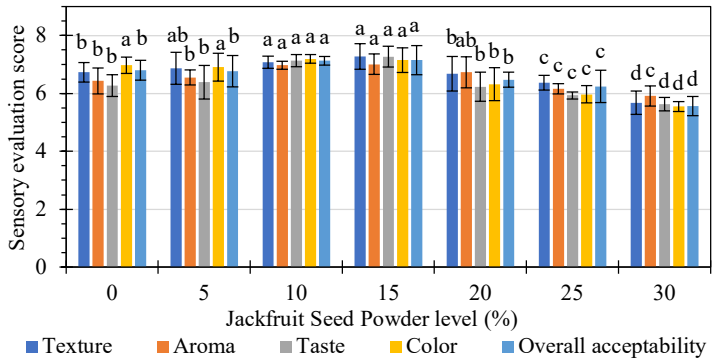
JSP (%)	*D* (mm)	*T* (mm)	*SR*	*H* (g)	*Note*
0	45.13 ± 0.05^{a}	6.53 ± 0.05^{a}	6.91 ± 0.06^{a}	1137.67 ± 24.68^{g}	*JSP: Jackfruit seed powder substitution; D: Diameter; T: Thickness; SR: Spread ratio; H: Hardness. Data are presented as mean ± standard deviation (n=3). Different superscript lowercase letters (a–g) within the same column indicate statistically significant differences ($p < 0.05$).*
5	44.92 ± 0.04^{b}	6.51 ± 0.03^{ab}	6.90 ± 0.04^{a}	1194.17 ± 12.00^{f}	
10	43.49 ± 0.04^{c}	6.46 ± 0.04^{bc}	6.74 ± 0.04^{b}	1302.17 ± 20.87^{e}	
15	43.25 ± 0.03^{d}	6.45 ± 0.02^{c}	6.71 ± 0.02^{b}	1423.83 ± 7.91^{d}	
20	43.20 ± 0.01^{d}	6.44 ± 0.03^{c}	6.70 ± 0.03^{b}	1598.67 ± 41.06^{c}	
25	43.00 ± 0.03^{e}	6.42 ± 0.03^{c}	6.69 ± 0.03^{b}	1641.67 ± 10.52^{b}	
30	42.73 ± 0.07^{f}	6.41 ± 0.03^{c}	6.67 ± 0.04^{b}	2079.00 ± 32.05^{a}	

The minor geometric differences observed between the 15% BGP formulation (Phase I) and the 0% JSP formulation (Phase II) reflect dough rheological responses to inter-batch heat flux dynamics over extended chronological runs (Table 5). Consequently, physical dimensions and spread ratios are evaluated relative to internal controls within each independent phase, rather than by direct cross-phase numerical comparison. Table 5 shows that increasing JSP incorporation from 0 to 30% increased cookie hardness from 1137.67 to 2079.00 g, while cookie diameter decreased from 45.13 to 42.73 mm, thickness decreased from 6.53 to 6.41 mm, and spread ratio declined from 6.91 to 6.67 ($p < 0.05$). The increased hardness indicates greater cookie firmness and may be associated with changes in water distribution and matrix structure following JSP incorporation. The starch and fiber fractions in JSP may contribute to these changes by influencing water availability and the structure of the dough; however, this proposed mechanism was not directly verified. Importantly, greater hardness does not necessarily indicate better product quality. Although moderate firmness may be desirable, the higher hardness at

elevated JSP levels coincided with lower sensory texture and overall acceptability scores [28], [29]. Therefore, the combined system provided a structural balance: BGP promoted softening and spreading, whereas JSP increased firmness and restricted expansion. So the 15% JSP sample had intermediate hardness (1423.83 g) and was selected as optimal.

3.7. Effect of Jackfruit Seed Powder on Sensory Evaluation

Figure 2 shows that sensory acceptance varied with JSP incorporation. The formulation containing 15% JSP achieved the highest numerical scores for texture (7.28 ± 1.16), aroma (7.01 ± 0.89), taste (7.27 ± 0.93), color (7.40 ± 0.66), and overall acceptability (7.35 ± 0.63). Based on the statistical grouping, overall acceptability did not differ significantly between the 15% and 10% JSP formulations (7.35 ± 0.63 and 7.13 ± 0.72, respectively; $p > 0.05$), whereas the 15% formulation scored significantly higher than the 20% formulation (6.47 ± 0.68; $p < 0.05$). Sensory scores generally declined at higher JSP incorporation levels, reaching their lowest values at 30% JSP. The increase in texture acceptance up to 15% JSP may reflect a more favorable textural balance, whereas excessive JSP incorporation may result in undesirable textural changes. Higher JSP levels were also associated with lower taste and color acceptance [28]. However, the mechanisms underlying these changes were not directly investigated. Therefore, 15% JSP was considered the preferred concentration based on its overall sensory performance, rather than being significantly superior to all neighboring formulations. Considering the sensory results alongside the other quality attributes, the formulation containing 15% BGP and 15% JSP was selected for further evaluation and designated as BJC.



Note:
Values are means ± SD.
Different lowercase letters (a, b, c, etc.) denote significant differences within each sensory attribute based on ANOVA and Tukey's test ($p < 0.05$).

Figure 2. *Sensory evaluation scores of BJC with different jackfruit seed powder levels.*

3.8. Nutritional profile and functional potential of the optimized cookie (BJC)

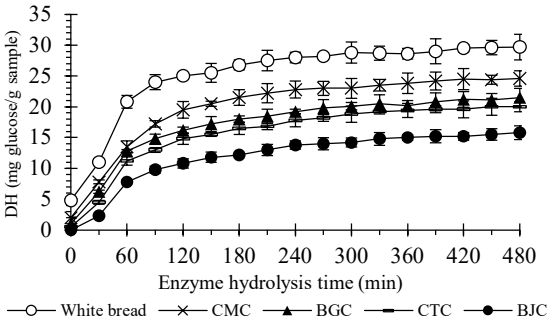
Table 6. *Nutritional composition of the optimized black garlic–jackfruit cookie and a commercial cookie.*

Components	Unit	BJC	Commercial Cookies (CMC)
Calories	kcal/100 g	479	516
Carbohydrate	%	63.8	65.5
Fat	%	21.2	25.7
Protein	%	8.23	5.63
Total fiber	%	6.33	2.59
Total polyphenols	mg GAE/100 g	231	-
Moisture	%	4.37	≤5%

The nutritional composition of the optimized cookie formulation (BJC, comprising 15% black garlic powder and 15% jackfruit seed powder) was compared with the commercial cookie (CMC) (Table 6). It should be emphasized that the nutritional comparison with the CMC serves as an external market

benchmark to evaluate the product from an end-consumer dietary perspective, rather than an analytical attribution study. Because commercial formulations involve confounding proprietary recipe differences, and due to the absence of multi-batch analytical replicates for the commercial sample, these nutritional parameters are reported as descriptive benchmarks. BJC had lower energy density than the commercial cookie (479 vs. 516 kcal/100 g), while carbohydrate contents were similar (63.8 vs. 65.5%). The lower energy value was associated with the formulation containing isomalt and jackfruit seed powder. BJC contained more protein (8.23%) than the commercial cookie (5.63%) and less fat (21.2 vs. 25.7%). The protein contributed by jackfruit seed and black garlic may have contributed to the observed textural differences [10], [26], [29]. Dietary fiber reached 6.33 g/100 g, approximately 2.4-fold that of the commercial cookie. The fiber-rich matrix may restrict enzyme access to starch and is consistent with the lower SHI observed [3], [20]. BJC contained 231 mg GAE/100 g total polyphenols and 4.37% moisture. Despite baking at 160°C, measurable radical-scavenging activity remained, likely reflecting contributions from black-garlic bioactive compounds and Maillard-derived melanoidins [4], [5], [30].

3.9. Starch hydrolysis kinetics and SHI



Note:
Samples include White bread (reference),
CMC: commercial cookies,
BGC: black garlic cookies,
CTC: control cookies,
BJC: black garlic–jackfruit cookies;
Error bars represent standard deviation (n = 3).

Figure 3. *Hydrolysis curves of starch in different cookie samples and white bread (reference).*

Table 7. *Parameters of the goñi et al. model characterizing starch hydrolysis kinetics.*

Sample	C∞ (mg/g)	k (1/min)	AUC (mg·min/g)	R^2	SHI (%)
White bread	29.74 ± 0.36[a]	0.0192 ± 0.0006[a]	12,185.7 ± 180.8[a]	0.982	100.00 ± 1.48[a]
CMC	23.86 ± 0.16[b]	0.0142 ± 0.0002[b]	9,769.9 ± 23.4[b]	0.990	80.18 ± 0.19[b]
BGC	21.24 ± 0.40[c]	0.0116 ± 0.0004[c]	8,359.5 ± 127.3[c]	0.994	68.60 ± 1.04[c]
CTC	20.01 ± 0.15[d]	0.0099 ± 0.0002[d]	7,554.4 ± 95.8[d]	0.996	62.00 ± 0.79[d]
BJC	15.82 ± 0.23[e]	0.0090 ± 0.0002[e]	5,659.8 ± 62.1[e]	0.997	46.45 ± 0.51[e]

All samples showed rapid starch hydrolysis during the first 90 min followed by a slower approach to a plateau (Figure 3, Table 7). BJC showed the lowest hydrolysis: SHI was 46.45%, compared with 80.18% for the commercial cookie and 62.00% for the control. Thus, the optimized formulation showed lower in vitro starch hydrolysis than both reference cookies. The lower SHI may be associated with type III resistant starch formed during steaming and 48 h cooling of the jackfruit seeds. Previous studies have reported that starch retrogradation can limit enzymatic access to starch [7], [31], [32]. Polyphenols may additionally interact with proteins and starch or influence digestive enzymes [33]. The denser, fiber-containing BJC matrix may also reduce accessible surface for enzyme–substrate contact; therefore, the lower SHI may reflect combined structural and compositional effects [20].

BJC showed RSA of 67.78 ± 0.23% after baking at 160 °C for 25 min. Antioxidant activity may reflect black-garlic sulfur compounds, jackfruit-seed phenolics, and melanoidins generated during Maillard browning [18], [26], [34].

4. Conclusions

This study demonstrated the feasibility of developing cookies containing 15% BGP and 15% JSP. BGP and JSP affected dough texture and cookie physical properties differently, with JSP incorporation increasing firmness and reducing adhesiveness and spread. The selected formulation (BJC) exhibited a hardness of 1423.83 g and an overall acceptability score of 7.35 ± 0.63. Its measured composition included 8.23% protein, 6.33 g/100 g dietary fiber, an energy value of 479 kcal/100 g, and total polyphenols of 231 mg GAE/100 g. The post-baking DPPH radical-scavenging activity was 67.78 ± 0.23%. The SHI of BJC was 46.45%, compared with 80.18% for the commercial cookie and 62.00% for the control. Although starch retrogradation, dietary fiber, and matrix structure may contribute to differences in starch hydrolysis, these mechanisms were not directly established in this study, and RS3 formation was not quantified. Overall, the findings support the potential use of BGP and JSP in value-added cookie development. Further studies on storage stability, starch structure, and in vivo responses are needed to validate the product's long-term quality and potential physiological effects.

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Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

The authors used ChatGPT for English-language editing and reviewed the manuscript content for accuracy and responsibility.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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