

Influences of Hot-Air Drying on the Functional Properties of Green Banana Pulp Flour and Its Application in Sponge Cake

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ABSTRACT

Large volumes of by-products generated during food processing are often discarded despite being rich in valuable components such as dietary fiber, antioxidants, and natural functional compounds. In banana starch production, green banana pulp (GBP) represents a fiber-rich residue that can be valorized as a functional flour in bakery applications. This study examined the effects of drying temperatures (50 °C, 60 °C, and 70 °C) and material loads (1.61 kg/m², 2.42 kg/m², and 3.23 kg/m²) on the physicochemical properties of GBP flour and evaluated its partial substitution for wheat flour (10 %, 20 %, and 30 %) in sponge cakes. Drying at 60 °C and 2.42 kg/m² yielded flour with desirable whiteness, the lowest browning index, and maximum soluble sugar retention, while maintaining stable crude fiber content. Incorporating GBP flour increased batter viscosity and crumb firmness but enhanced the dietary fiber content of cakes. The 10% substitution level achieved the most favorable balance between structure, sensory acceptability, and nutritional improvement. Overall, GBP flour is demonstrated as a sustainable, fiber-enriching ingredient that enhances the nutritional profile of sponge cakes while promoting the value-added utilization of agro-industrial by-products and supporting waste reduction in food processing.

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1. Introduction

The banana (*Musa* spp., Cavendish group) is one of the most widely consumed tropical fruits, contributing approximately 15% of total global fruit production, with an annual output of around 110 million tons [1]. It is a rich source of resistant starch, dietary fiber, and vitamins, which have been associated with beneficial effects such as cholesterol reduction, glycemic regulation, and improved gastrointestinal function [2]. However, the firm texture and astringent taste of unripe bananas limit their consumption, underscoring the need for processing into stable and acceptable food ingredients [3].

One underexploited resource generated during starch extraction is green banana pulp (GBP), which is particularly valued as a source of dietary fiber and nutrients associated with satiety regulation and weight management [4]. Hot-air convective drying is widely applied to transform GBP into flour with enhanced stability and prolonged shelf life [5]. The drying parameters (air temperature and material load) play a decisive role in determining the quality of the product, such as color, nutrient retention, and functional properties [6]. Both drying temperature (40 – 60 °C) and material load (0.057 – 0.113 g/cm²) significantly affected bioactive retention and microstructure in dried radish Sango microgreens [7]. Optimizing temperature was crucial to balance drying kinetics while preserving color and nutrient quality in banana products [8], [9].

Sponge cakes are widely consumed bakery products but typically contain little dietary fiber. Incorporating GBP flour into sponge cakes offers a practical strategy to enhance their nutritional value without compromising consumer acceptability. Previous studies have shown that partially replacing wheat flour with banana-based flours increases fiber content, phenolic compounds, and antioxidant activity, with only minor effects on texture and color attributes [10], [11]. These findings demonstrate

the promise of banana-derived ingredients for bakery applications; however, evidence specifically concerning GBP flour, particularly when sourced as a by-product of starch processing, remains limited.

Therefore, this study aimed to suitably determine the drying process of GBP under controlled hot-air conditions and to evaluate how drying temperature and material load influence its physicochemical and functional properties. Additionally, GBP flour was partially substituted for wheat flour in sponge cake formulations to assess its impact on the physical, textural, and sensory qualities of the final product.

2. Materials and Methods

2.1. Materials

Green Cavendish bananas were sourced from Duc Bao farm (Binh Duong, Vietnam), approximately 3.5 months after flowering. The fruits were stored at 10–12 °C until further use.

Ingredients for sponge cake preparation included wheat flour (Bakers' Choice No. 8, Vietnam), refined sugar (Bien Hoa, Vietnam), unsalted butter (Imperial, Thailand), whole milk (Vinamilk, Vietnam), and commercial chicken eggs (Ba Huan, Vietnam).

Analytical-grade chemicals and reagents (Xilong, China) were supplied by SBC Trading and Service Co., Ltd. (Ho Chi Minh, Vietnam) and used for sample preparation and proximate analysis. Glucose (Sigma-Aldrich, USA) was employed as the standard for sugar quantification.

2.2. Methods

2.2.1. Preparation of GBP flour

Green bananas were washed, peeled, and sliced. The pulp was immersed in a 0.1% NaHSO₃ solution for 30 min, then rinsed and homogenized with distilled water (1:5 w/v). The homogenate was filtered, and the residue was collected for drying. Drying was carried out at temperatures of 50, 60, and 70 °C with material loads of 1.61, 2.42, and 3.23 kg/m² until the moisture content was reduced to below 10%. The dried pulp was ground, sieved (0.5 mm mesh), and stored in a desiccator for subsequent analyses.

2.2.2. Preparation of sponge cake

Wheat flour was partially substituted with GBP flour at 10%, 20%, and 30% (w/w). The flour blend was mixed with egg yolks, a butter–milk mixture (50 °C), and vanilla extract. Egg whites were whipped with sugar until soft peaks formed and then gently folded into the batter. The sponge cakes were baked at 150 °C for 60 min in pans (16×16×8 cm) and allowed to cool for 1 h prior to evaluation.

2.2.3. Determination of proximate composition

Proximate composition of GBP flour was analyzed following standard AOAC procedures [12]. Moisture content was determined by NFTA 2.2.2.5, crude protein by the modified Kjeldahl method (AOAC 984.13), crude fat by petroleum ether extraction (AOAC 945.16), and ash by incineration (AOAC 942.05). Total carbohydrates were calculated by difference, and crude fiber content was measured according to AOAC 978.10.

2.2.4. Color measurement

The color parameters (L*, a*, b*) of GBP flour and sponge cake were recorded using a Minolta CR-400 Chroma Meter (Konica Minolta, Japan). Whiteness index (WI), browning index (BI), hue angle (H°), and chroma (C*) were calculated according to the following Eq. (1) [13], [14].

$$WI = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}}; BI = \frac{100(X - 0.31)}{0.17}, \text{ with: } X = \frac{a^* + 1.75L^*}{5.645L^* + a^* - 3.012b^*} \quad (1)$$

2.2.5. Determination of soluble sugar content

Soluble sugar content was determined using the phenol–sulfuric acid method [15], [16]. A 0.5 mL sample solution (~10⁴ µg/mL) was mixed with 0.5 mL of 5% phenol and 2.5 mL of concentrated H₂SO₄ and allowed to stand at room temperature for 20 min. Absorbance was measured at 490 nm using a UV–

Vis spectrophotometer (Model 7305, Jenway, UK). Glucose was used as the standard, and total sugar content was calculated according to Eq. (2):

$$G (\%) = \frac{C_1}{C} \times 100 \quad (2)$$

where C_1 is the sugar concentration in the sample solution ($\mu\text{g/mL}$), and C is the concentration of the original sample suspension ($\mu\text{g/mL}$).

2.2.6. Moisture sorption isotherm

GBP flour was equilibrated at $25 \pm 2^\circ\text{C}$ in sealed desiccators containing saturated salt solutions (KOH, KCl, NaCl, K_2CO_3 , and CH_3COOK), corresponding to water activity (a_w) values ranging from 0.11 to 0.90. Equilibrium moisture content was recorded, and the sorption data were fitted to the Guggenheim–Anderson–de Boer (GAB) model [17]. The GAB equation is presented as Eq. (3):

$$MC = \frac{w_m C K a_w}{(1 - K a_w)(1 - K a_w + C K a_w)} \quad (3)$$

where MC is the equilibrium moisture content, a_w is water activity, w_m is the monolayer moisture content, and K and C are dimensionless GAB sorption constants.

2.2.7. Water absorption capacity (WAC) and oil absorption capacity (OAC)

One gram of flour was mixed with 25 mL of distilled water or canola oil, vortexed for 1 min, and allowed to stand at room temperature. The mixtures were centrifuged at 3,000 rpm for 20 min, and the supernatant was discarded [18]. WAC and OAC were expressed as grams of water or oil absorbed per 100 g of sample (dry basis).

2.2.8. Swelling power

Flour samples (0.25 g) were suspended in 25 mL of distilled water, mixed well for 30 s, and heated at 70, 80, or 90 °C for 20 min. After cooling to room temperature, samples were centrifuged at 3,000 rpm for 10 min [19]. The supernatant was discarded, and the sediment was weighed.

2.2.9. Texture profile analysis of sponge cakes

Sponge cake texture was evaluated 1 h after baking using a TA-XT2i texture analyzer (Stable Microsystems, Surrey, UK) [20]. Cubic samples (30×30×30 mm) were subjected to double compression (30% deformation) using a 25 mm cylindrical aluminum probe. Texture parameters, including hardness, cohesiveness, springiness, and chewiness, were computed from the TPA curves [21].

2.2.10. Determination of specific volume

Specific volume was determined using the rapeseed displacement method [22]. After cooling, cakes were weighed, and their volume was measured by the displaced rapeseed volume in a standardized container. Specific volume was calculated according to Eq. (4):

$$\text{Specific volume (cm}^3\text{/g)} = \frac{\text{Sponge cake volume}}{\text{Sponge cake weight}} \quad (4)$$

2.2.11. Sensory evaluation

Sensory evaluation was conducted within 12 h after baking using a 9-point hedonic scale (1 = dislike extremely, 9 = like extremely). Thirty-two untrained panelists assessed the color, flavor, texture, and overall acceptability of the samples.

2.2.12. Statistical analysis

Each single-factor experiment was performed in triplicate, and data were expressed as mean \pm standard deviation. One-way analysis of variance was conducted using SPSS software (version 22.0, IBM Corp., Armonk, NY, USA). Differences were considered statistically significant at $P < 0.05$.

3. Results and Discussion

3.1. The effects of drying temperature on the properties of GBP flour

3.1.1. Moisture content

The initial moisture content of GBP was approximately 81.33%. Moisture loss was recorded at 30-min intervals until a target moisture content of about 5% was reached (Figure 1a).

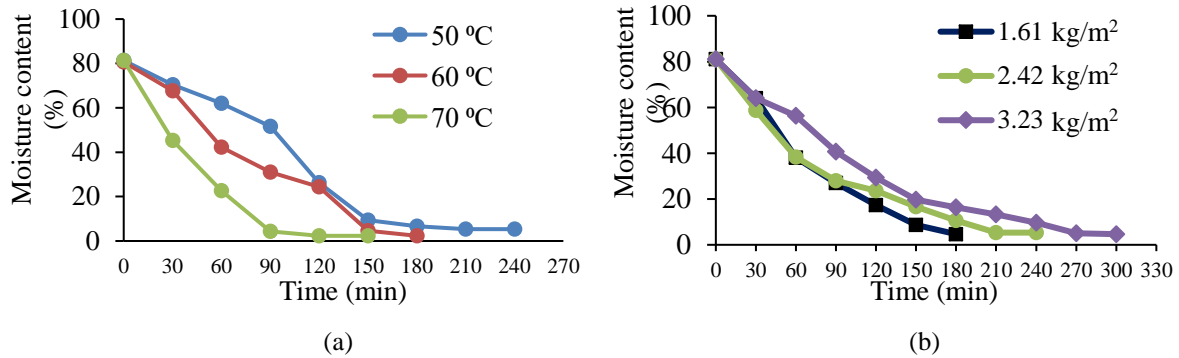


Figure 1. Drying curve of GBP flour at different temperatures.

At 50, 60, and 70 °C, drying times were 4 h, 3 h, and 2.5 h, respectively, and the corresponding final moisture contents were 5.33%, 2.33%, and 2.33%. Across all temperatures, moisture content decreased rapidly during the first 1–2 h, then approached a quasi-constant period. The fastest moisture removal occurred at 70 °C, attributable to a larger vapor-pressure gradient and enhanced heat transfer from the drying air to the material, which together accelerated surface evaporation and internal diffusion. Thus, increasing temperature shortened drying time while achieving comparable final moisture.

3.1.2. Whiteness, browning index, soluble sugars, and crude fiber

Whiteness and browning index did not differ significantly between 50 and 70 °C ($P > 0.05$), whereas 60 °C yielded the highest whiteness and the lowest browning index ($P < 0.05$) (Table 1). Excessive heat or prolonged exposure promotes non-enzymatic browning [23], increasing browning.

Table 1. Effect of drying temperature on whiteness and composition of GBP flour.

Temperature (°C)	Whiteness	Browning index	Soluble sugar concentration (µg/mL)	Soluble sugar content (%)	Crude fiber (%)
Control (d.b.)	69.95 ± 0.56 ^c	27.22 ± 1.04 ^a	183.75 ± 1.53 ^a	1.84 ± 0.02 ^a	2.28 ± 0.02 ^a
50	81.48 ± 0.45 ^b	16.86 ± 0.61 ^b	119.73 ± 1.63 ^c	1.20 ± 0.02 ^c	2.24 ± 0.06 ^a
60	83.05 ± 0.67 ^a	15.04 ± 0.91 ^c	182.56 ± 3.24 ^a	1.83 ± 0.03 ^a	2.26 ± 0.03 ^a
70	81.81 ± 0.26 ^b	16.49 ± 0.29 ^b	137.23 ± 1.42 ^b	1.37 ± 0.01 ^b	2.27 ± 0.03 ^a

Different superscript letters (a, b, c, ...) within the same parameter indicate statistically significant differences ($P < 0.05$). d.b.: dry basis.

For composition, total soluble sugars were highest at 60 °C ($P < 0.05$). At higher temperatures and/or longer residence, Maillard reactions can deplete reducing sugars, lowering total sugars. Crude fiber did not differ among temperatures ($P > 0.05$). Overall, 60 °C offered a reasonable drying time (~3 h) while maintaining superior color and higher sugar retention without affecting crude fiber.

3.2. The effects of material load on the properties of GBP flour

3.2.1. Moisture content

At 60 °C, three different material loads were compared to evaluate their influence on the moisture removal kinetics of GBP (Figure 1b). As expected, drying time increased proportionally with loading density, requiring approximately 3, 4, and 5 h, respectively, to reach the target moisture content of 5%. The corresponding final moisture values were 4.67%, 5.33%, and 4.67%. The fastest moisture reduction

was achieved at the lowest loading density, primarily due to improved air circulation between the material layers and a thinner bed depth, which enhanced convective heat transfer and mass diffusion. At higher material loads, the thicker sample bed restricted airflow, thereby reducing the effective surface area available for evaporation and increasing internal resistance to moisture migration. This behavior is consistent with Fick's second law of diffusion, which describes moisture migration as a function of internal concentration gradients. When the bed thickness or bulk density increases, the path length for moisture diffusion also increases, resulting in lower effective diffusivity.

In summary, reducing the material load improved heat and mass transfer efficiency, shortened the drying period, and yielded a more uniform moisture distribution throughout the sample matrix. However, lower material loads reduce dryer throughput and increase specific energy consumption per unit of product. Therefore, the subsequent analysis aimed to identify an optimal trade-off between drying efficiency and production capacity to ensure both quality and economic feasibility.

3.2.2. Whiteness, browning index, soluble sugars, and crude fiber

The influence of material load on the whiteness, browning index, soluble sugar content, and crude fiber content of GBP flour is presented in Table 2. No significant differences were observed in browning index among the three material loads ($P > 0.05$), whereas whiteness values differed significantly ($P < 0.05$). The highest whiteness and lowest browning index were obtained at 1.61 kg/m². Similar to the effect of elevated drying temperatures, higher material loads with extended drying times likely accelerated the Maillard reaction, leading to reduced whiteness and increased browning in GBP flour.

Table 2. Effect of material load on properties of GBP flour.

Material load (kg/m ²)	Whiteness	Browning index	Soluble sugar concentration (µg/mL)	Soluble sugar content (%)	Crude fiber (%)
Control (d.b.)	69.95 ± 0.56 ^c	27.22 ± 1.05 ^a	168.68 ± 0.97 ^a	1.69 ± 0.01 ^a	2.17 ± 0.03 ^a
1.61	82.09 ± 0.56 ^b	16.21 ± 0.23 ^b	157.21 ± 2.03 ^b	1.57 ± 0.02 ^b	2.16 ± 0.02 ^a
2.42	83.14 ± 0.53 ^a	14.93 ± 0.75 ^b	142.44 ± 1.59 ^c	1.42 ± 0.02 ^c	2.15 ± 0.02 ^a
3.23	82.76 ± 0.41 ^{ab}	14.99 ± 0.53 ^b	127.75 ± 1.34 ^d	1.28 ± 0.01 ^d	2.14 ± 0.03 ^a

Different superscript letters (a, b, c, ...) within the same column indicate statistically significant differences ($P < 0.05$). d.b.: dry basis.

Material load significantly affected the soluble sugar content of GBP flour ($P < 0.05$), with the highest value at 1.61 kg/m², indicating a clear decreasing trend. In contrast, crude fiber content did not differ significantly among the three loads ($P > 0.05$). Increasing the load by 1.5 times (from 1.61 to 2.42 kg/m²) required only about 60 additional minutes to reach a final moisture content of about 5.33%, without notable differences in color, browning index, or crude fiber content. Therefore, 2.42 kg/m² was determined as the most suitable loading density for drying GBP flour, as it allowed processing of a larger pulp quantity per cycle, improving production efficiency and reducing operational costs.

3.3. Moisture sorption isotherm analysis for storage of GBP flour

3.3.1. The effects of equilibrium relative humidity on equilibrium moisture content (EMC) of GBP flour

This experiment evaluated the effect of different equilibrium relative humidity (ERH) levels on the stability of GBP flour stored at room temperature (25 ± 2 °C), as shown in Figure 2.

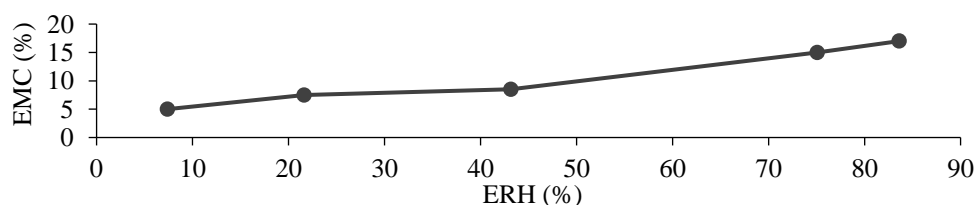


Figure 2. The influence of environmental ERH on the EMC of GBP powder at room temperature.

The initial moisture content of the flour was 7.33%. During storage, the EMC increased slightly from 7.5% to 8.5% as ERH rose from 21.61% to 43.17%. At an ERH of 7.38%, the EMC decreased to 5%, indicating water loss through desorption. Conversely, as ERH increased from 21.61% to 83.62%, the flour exhibited moisture adsorption, with EMC rising from 7.5% to 17%. Thus, under constant temperature, EMC increased with ERH, displaying the characteristic sigmoidal pattern of a type II sorption isotherm [24], [25]. This EMC–ERH relationship was consistent with previous findings for potato starch [24], oat and rice flours [26]. However, a high ERH (> 50%) promotes excessive moisture adsorption, whereas a very low ERH (< 20%) induces desorption. Therefore, GBP flour should be stored under intermediate humidity conditions to ensure stability.

The GAB model was applied to describe the moisture sorption isotherm of GBP flour (Table 3). The monolayer moisture content (w_m), estimated from the GAB equation ($y = -0.1268x^2 + 0.1612x + 0.0024$; $R^2 = 0.9843$), was 6.06%. To ensure maximum storage stability and minimize deterioration, the moisture content of GBP flour should be maintained close to the w_m value determined by the GAB equation.

Table 3. Estimated parameters of GAB model.

Models	w_m	C	K	R^2
GAB	6.0631	88.3771	0.7776	0.9843

3.3.2. Color value, whiteness, and browning index

The effect of ERH variation on the color parameters of GBP flour is presented in Table 4. As ERH increased, the whiteness index gradually declined, whereas the browning index exhibited a corresponding rise, indicating a progressive darkening of the flour. These variations were not statistically significant ($P > 0.05$) within the intermediate ERH range of 21.61% – 75.09%, suggesting relative color stability under moderate humidity conditions. However, at the highest ERH level (83.62%), both the whiteness and browning index differed significantly ($P < 0.05$) compared with samples maintained at lower ERH levels (7.38% – 43.17%).

Table 4. Effect of ERH on the color values, whiteness, and browning index of GBP flour.

ERH (%)	L^*	a^*	b^*	Whiteness	Browning index
7.38	86.18 ± 0.58^d	0.56 ± 0.45^e	11.68 ± 0.63^a	81.90 ± 0.83^c	14.71 ± 0.97^a
21.61	87.83 ± 0.22^a	0.61 ± 0.33^d	10.72 ± 0.06^b	83.76 ± 0.20^a	13.23 ± 0.08^b
43.17	87.60 ± 0.52^{ab}	0.67 ± 0.04^c	10.88 ± 0.39^b	83.49 ± 0.55^a	13.53 ± 0.54^b
75.09	87.14 ± 0.25^{bc}	1.09 ± 0.22^b	10.83 ± 0.22^b	83.15 ± 0.29^{ab}	13.90 ± 0.31^{ab}
83.62	86.70 ± 0.34^c	1.28 ± 0.62^a	10.79 ± 0.22^b	82.82 ± 0.39^b	14.07 ± 0.30^a

Different superscript letters (a, b, c, ...) within the same column indicate statistically significant differences ($P < 0.05$).

This distinct shift in color parameters at elevated ERH can be attributed to increased water activity (a_w), which enhances the mobility of reactants and promotes non-enzymatic browning reactions [27]. Such reactions are favored when sufficient moisture is available to facilitate molecular rearrangements, but not so high as to cause dilution of reactants. Conversely, at ERH below 20%, the system tends to undergo moisture desorption, which can induce slight surface whitening or uneven light scattering due to microstructural dehydration and increased porosity.

Overall, GBP flour retains acceptable color stability across a broad humidity spectrum up to ~75% ERH, beyond which accelerated browning may occur. Therefore, storage under controlled humidity conditions ($\leq 50\%$ ERH) is recommended to maintain optimal color quality and minimize pigment degradation or Maillard-induced darkening.

3.3.3. Soluble sugar content and crude fiber content

As ERH increased, a progressive decline in total soluble sugar was observed (Table 5). Compared with the control, the smallest reduction occurred at the lowest ERH, while the most pronounced loss was recorded at 83.62%. When a_w increases, the mobility of reducing sugars and amino groups is enhanced, which facilitates condensation and subsequent polymerization reactions leading to the formation of melanoidins [27]. A fraction of soluble sugars is consumed as precursors in these reactions, resulting in a measurable decrease in total sugar content. In addition, at higher ERH, partial hydrolytic degradation of carbohydrates may also occur, further contributing to sugar loss through the formation of intermediate aldehydes and organic acids. In contrast, the crude fiber content remained statistically unaffected ($P > 0.05$) across all ERH levels. This stability can be explained by the chemical inertness and high structural rigidity of cell-wall polysaccharides such as cellulose and lignin, which exhibit limited hygroscopic expansion or degradation within the tested humidity range. Thus, ERH variations predominantly influence the amorphous carbohydrate fraction rather than the insoluble fiber matrix.

Table 5. Effect of equilibrium relative humidity on soluble sugar content and crude fiber content of GBP flour.

ERH (%)	Soluble sugar concentration ($\mu\text{g/mL}$)	Soluble sugar content (%)	Crude fiber (%)
Control (d.b.)	101.77 ± 0.77^a	1.02 ± 0.01^a	1.80 ± 0.01^a
7.38	99.98 ± 1.34^b	1.00 ± 0.01^b	1.76 ± 0.07^a
21.61	96.64 ± 1.10^c	0.97 ± 0.01^c	1.73 ± 0.01^a
43.17	93.94 ± 1.33^d	0.94 ± 0.01^d	1.75 ± 0.04^a
75.09	89.94 ± 1.15^e	0.90 ± 0.01^e	1.73 ± 0.01^a
83.62	57.74 ± 1.19^f	0.58 ± 0.01^f	1.74 ± 0.04^a

Different superscript letters (a, b, c, ...) within the same column indicate statistically significant differences ($P < 0.05$). d.b.: dry basis.

Overall, maintaining GBP flour at a moisture content below the monolayer value (approximately 6.1%) is essential for minimizing sugar degradation and ensuring long-term stability. Under these conditions, the material remains within the range of minimal water activity that suppresses both Maillard kinetics and microbial proliferation, thereby preserving its nutritional and functional quality.

3.4. Proximate analysis and functional properties of GBP flour

Based on the previous experiments, GBP was dried at 60 °C with a material load of 2.42 kg/m², which was identified as the most suitable condition for maintaining both sensory quality and nutritional integrity. The proximate compositions of fresh GBP and GBP flour are summarized in Table 6.

Table 6. Chemical composition and functional properties of fresh GBP, GBP flour, and wheat flour.

Parameters	Fresh GBP	GBP flour	Wheat flour
Carbohydrate (%)	24.72 ± 0.55	87.75 ± 0.75	n.a.
Reducing sugar content (%)	1.65 ± 0.07	0.95 ± 0.003	n.a.
Crude fiber (%)	2.35 ± 0.11	2.19 ± 0.08	n.a.
Protein (%)	1.74 ± 0.02	3.24 ± 0.17	n.a.
Lipid (%)	0.15 ± 0.01	0.55 ± 0.01	n.a.
Ash (%)	1.11 ± 0.10	1.12 ± 0.14	n.a.
Moisture (%)	72.33 ± 0.58	7.33 ± 0.58	n.a.
WAC (g/g)	n.a.	3.68 ± 0.03^a	2.43 ± 0.01^b
OAC (g/g)	n.a.	3.09 ± 0.21^a	2.69 ± 0.07^a

Swelling power (%)	70 °C	n.a.	6.69 ± 0.12 ^e	9.73 ± 0.02 ^d
	80 °C	n.a.	15.81 ± 0.08 ^b	9.82 ± 0.02 ^d
	90 °C	n.a.	16.20 ± 0.16 ^a	12.36 ± 0.16 ^c

Different superscript letters (a, b, c, ...) within the same row indicate statistically significant differences ($P < 0.05$). n.a.: not applicable.

Fresh GBP contained a high moisture level (72.33%), which inherently limited its stability and industrial applicability. In contrast, GBP flour exhibited a total carbohydrate content of 87.75% (dry basis), while reducing sugars decreased to 0.95%. The decline in reducing sugars likely reflects partial participation in Maillard reactions and mild thermal degradation during dehydration. Crude fiber remained relatively constant, suggesting that the structural polysaccharides were largely unaffected by the applied heat. Minor increases in protein and lipid levels were also noted, which may be attributed to compositional concentration effects as moisture was removed. Overall, the significant reduction in water content enhances shelf stability, microbial safety, and functional consistency of the flour.

Functionally, GBP flour displayed a significantly greater WAC than wheat flour ($P < 0.05$). This superior hydration capacity is attributed to the high content of hydrophilic macromolecules, notably non-starch polysaccharides and proteins, that interact with water through both hydrogen bonding and polar amino acid residues. In contrast, the lower WAC of wheat flour could result from its denser starch granules and restricted surface accessibility caused by gluten network formation [28].

GBP flour exhibited slightly higher OAC values than wheat flour, although the difference was not statistically significant ($P > 0.05$). The enhanced OAC of GBP flour is possibly associated with its amphiphilic protein components, which contain non-polar side chains capable of hydrophobic interactions with lipids, thereby improving flavor retention and mouthfeel in formulated foods [29].

Regarding swelling power, GBP flour exhibited a temperature-dependent pattern, reaching its maximum value (16.2%) at 90 °C and its lowest (6.69%) at 70 °C. The higher swelling capacity of GBP flour compared to wheat flour suggests partial starch modification and enhanced water-binding by soluble fibers formed during thermal processing [29]. These hydrophilic components can form a gel-like network that retains water and improves viscoelasticity at elevated temperatures.

In summary, the results indicate that GBP flour possesses favorable hydration and functional characteristics, making it a potential ingredient for bakery and composite flour formulations. Its high WAC and thermal swelling ability highlight its potential role as a natural water-retaining and texture-enhancing agent, while its stable fiber content supports the development of fiber-enriched and nutritionally improved food products.

3.5. Application of GBP flour in sponge cake formulations

3.5.1. Color and physicochemical properties

Figure 3 illustrates the cross-sectional appearance of sponge cakes prepared with varying substitution levels of GBP flour (0, 10, 20, and 30%) for wheat flour. The instrumental color parameters are summarized in Table 7. As the proportion of GBP flour increased, the crumb color gradually darkened, indicating that the visual characteristics of the cakes were strongly influenced by the intrinsic color of the GBP material and its compositional interactions within the batter matrix.

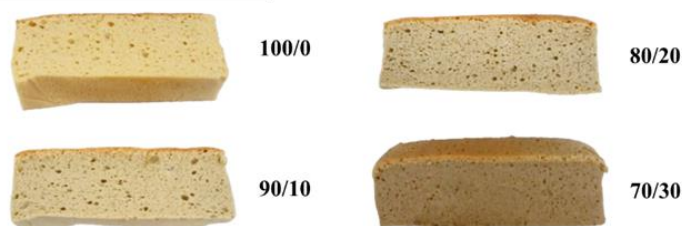


Figure 3. Cross-sections of sponge cakes formulated with different substitution levels of GBP flour.

Notes: 100/0, 90/10, 80/20, and 70/30 represent formulations in which 0%, 10%, 20%, and 30% of wheat flour were replaced with GBP flour, respectively.

The lightness (L^*) of the sponge cakes decreased significantly ($P < 0.05$) with increasing GBP flour substitution, demonstrating a progressive shift toward darker tones. The control sample exhibited the highest L^* value, corresponding to a bright yellow crumb, while the 30% substitution sample displayed the lowest L^* , indicative of intense browning. Similarly, hue angle (H°), which represents the overall color tone, declined significantly ($P < 0.05$) as GBP flour content increased, reflecting a transition from a yellowish hue to a reddish-brown appearance. The chroma (C^*), a measure of color saturation, also differed significantly between the control and GBP-enriched cakes ($P < 0.05$), suggesting changes in pigment intensity associated with the incorporation of GBP flour.

Table 7. Color and physical characteristics of sponge cakes incorporated with different levels of GBP flour.

GBP flour substitution (%)	0	10	20	30
L^*	79.98 ± 2.19^a	75.34 ± 0.95^b	71.71 ± 1.73^c	70.29 ± 1.80^d
a^*	1.03 ± 0.31^b	0.34 ± 0.29^c	1.10 ± 0.40^b	1.89 ± 0.43^a
Color b^*	29.48 ± 1.89^a	21.51 ± 1.74^b	20.88 ± 0.92^b	21.17 ± 0.82^b
Chroma	29.51 ± 1.90^a	21.51 ± 1.74^b	20.91 ± 0.90^b	21.26 ± 0.79^b
Hue	89.08 ± 0.79^a	88.02 ± 0.53^b	86.95 ± 1.19^c	84.86 ± 1.29^d
Moisture (%)	47.17 ± 1.47^a	45.33 ± 1.10^{ab}	44.83 ± 1.47^b	44.00 ± 0.89^b
Specific volume (cm^3/g)	2.40 ± 0.07^a	2.11 ± 0.10^b	1.81 ± 0.06^c	1.16 ± 0.16^d
Hardness (N)	355.34 ± 27.58^c	333.57 ± 12.84^c	442.76 ± 27.79^b	747.31 ± 36.31^a
Cohesiveness	0.76 ± 0.02^a	0.76 ± 0.01^a	0.78 ± 0.01^a	0.72 ± 0.03^b
Springiness	0.91 ± 0.02^a	0.89 ± 0.04^a	0.90 ± 0.02^a	0.86 ± 0.02^b
Plasticity (N)	269.36 ± 21.28^c	254.46 ± 10.99^c	343.51 ± 18.31^b	534.97 ± 46.73^a
Chewiness (N)	243.96 ± 17.70^c	225.19 ± 12.03^c	309.00 ± 17.64^b	457.75 ± 45.16^a

Different superscript letters (a, b, c, ...) within the same row indicate statistically significant differences ($P < 0.05$).

The control exhibited the highest H° and C^* values primarily due to its elevated b^* coordinate, which yielded a vivid yellow coloration. In contrast, the cake containing 30% GBP flour had the highest a^* value and the lowest H° and C^* , corresponding to a darker brown crumb. This darkening can be attributed to the polyphenolic composition of GBP flour (0.71 ± 0.03 mg GAE/mL). Fiber - polyphenol interactions can influence pigment retention and stability during thermal processing [30]. Specifically, the formation of hydrogen and hydrophobic bonds between polyphenols and cell-wall polysaccharides (e.g., cellulose and pectin) may alter the optical properties of the crumb and enhance color uniformity.

The moisture content of the cakes decreased slightly as the substitution level increased, reaching 44% at 30% replacement. However, the difference between the control and the 10% substitution was not statistically significant ($P > 0.05$), indicating minimal water loss at lower inclusion levels.

The specific volume decreased markedly ($P < 0.05$) with increasing GBP substitution to $1.16 \text{ cm}^3/\text{g}$ in the 30% formulation. This decline can be explained by the high WAC of GBP flour, which increases batter viscosity and restricts air incorporation and expansion during mixing and baking. Similar findings were reported in a previous study that the starch - gluten network in wheat flour-based batters provides structural elasticity essential for gas retention [31]. The introduction of GBP flour, rich in non-gluten polysaccharides and dietary fibers, dilutes gluten concentration, increases matrix resistance, and impedes bubble coalescence, leading to a denser crumb structure. The present results revealed that increasing GBP levels resulted in greater hardness. Higher fiber content disrupts the viscoelastic balance of the gluten-starch matrix and competes for water, reducing aeration and cake volume [32]. Nonetheless, at 10% substitution, the textural parameters, including cohesiveness and springiness, remained statistically comparable to the control ($P > 0.05$), suggesting that partial incorporation of GBP flour can be achieved without compromising the structural integrity of the sponge cake.

The inclusion of GBP flour increased chewiness and plasticity, likely due to the reinforcing effect of insoluble fibers and the enhanced water-holding capacity. Dietary fibers can also alter the secondary structural patterns of gluten proteins [33]. When wheat flour is partially replaced with GBP flour, fiber competes with both gluten proteins and starch for available water, resulting in incomplete starch gelatinization and increased cake firmness. Furthermore, fiber weakens the gluten matrix, which ultimately prevents the formation of the gluten network because of steric hindrance [34].

Importantly, despite these mechanical differences, all cake samples maintained satisfactory visual appearance and uniform height (Figure 3), indicating that GBP flour substitution up to 30% did not cause visible structural collapse. This suggests good compatibility between GBP flour and wheat flour in composite formulations, particularly at moderate substitution levels ($\leq 10\%$), where functional enrichment can be achieved without deteriorating technological or sensory quality.

3.5.2. Sensory evaluation

Overall, partial substitution of wheat flour with GBP flour exerted a minimal impact on flavor and taste perception (Table 8). The color acceptability significantly decreased ($P < 0.05$) as GBP flour levels increased, reflecting consumers' preference for the typical light-yellow appearance of conventional sponge cakes. This reduced visual appeal likely stems from panelists' familiarity bias, as darker-colored bakery products are often perceived as less typical or overbaked, despite being nutritionally enhanced.

Table 8. Sensory evaluation of sponge cakes incorporated with different levels of GBP flour.

GBP substitution (%)	Color	Flavor	Taste	Texture	Overall
0	7.75 ± 1.08 ^a	6.78 ± 1.56 ^a	6.47 ± 1.41 ^b	6.84 ± 1.44 ^a	6.88 ± 1.24 ^a
10	6.53 ± 1.08 ^b	7.22 ± 1.21 ^a	7.25 ± 1.32 ^a	7.09 ± 1.20 ^a	7.22 ± 1.10 ^a
20	6.65 ± 1.10 ^b	6.84 ± 1.32 ^a	7.13 ± 0.94 ^{ab}	6.94 ± 1.16 ^a	7.09 ± 1.09 ^a
30	6.12 ± 1.04 ^b	6.75 ± 1.32 ^a	6.59 ± 1.39 ^{ab}	6.66 ± 1.42 ^a	6.66 ± 1.21 ^a

Different superscript letters (a, b, c, ...) within the same column indicate statistically significant differences ($P < 0.05$).

Regarding flavor and taste, panelists reported no significant differences among treatments. Although GBP flour inherently carries a mild green-banana note, this aroma was effectively masked by the vanilla essence in the formulation, resulting in similar sensory scores across samples. However, a few participants mentioned a subtle astringent aftertaste, which could be attributed to residual polyphenolic compounds naturally present in GBP flour. These compounds are known to impart mild astringency through interactions with salivary proteins, although at low inclusion levels, their perception remained negligible.

In terms of texture perception, the 10% formulation achieved the highest overall acceptability score, maintaining desirable softness and mouthfeel comparable to the control. The improved texture may be related to the water-holding and gel-forming ability of GBP flour, which contributed to crumb elasticity while avoiding excessive hardness. At a higher inclusion level (30%), the denser crumb and elevated fiber content likely reduced aeration and springiness, thereby lowering texture preference.

From a nutritional and practical perspective, incorporating GBP flour at a 10% replacement ratio appears appropriate. This level enriches the product with dietary fiber while maintaining sensory quality and consumer appeal. Considering that the recommended dietary fiber intake for Vietnamese adults is approximately 20 g per day, and given the existing intake from fruits and vegetables, such a substitution can meaningfully contribute to fiber consumption without altering product desirability.

In conclusion, a 10% GBP flour substitution successfully balances technological performance, sensory acceptability, and nutritional enhancement, demonstrating the potential of GBP as a functional ingredient in bakery applications. This approach aligns with sustainable food processing trends, where underutilized agricultural by-products are valorized into nutrient-rich, consumer-acceptable products.

4. Conclusions

Drying green banana pulp at 60 °C and 2.42 kg/m² produced flour with optimal quality. The GAB model identified a critical moisture level below 6.06% for stable storage. Drying conditions and relative humidity had no significant effect on crude fiber content. GBP flour showed superior water and oil absorption capacities and greater swelling power than wheat flour. Incorporating GBP flour into sponge cakes improved their fiber content without compromising texture or flavor. Notably, the 10% substitution level achieved the best balance between structure, sensory quality, and nutritional enhancement. Overall, this study establishes green banana pulp flour as a sustainable, fiber-rich ingredient suitable for bakery applications, contributing to both value-added utilization of agro-industrial by-products and development of healthier food products.

Conflict of Interest

The authors declare no conflict of interest.

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