A PRELIMINARY STUDY: EFFECTS OF DIFFERENT BAMBANGAN FRUIT PROCESSING METHODS ON THE TEXTURE AND SENSORY PROFILE OF DARK CHOCOLATE PRALINE FILLED WITH BAMBANGAN FRUIT GANACHE

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ABSTRACT – *This study investigates how bambangan (Mangifera pajang) processing method and formulation composition influence the textural and sensory properties of dark chocolate pralines containing white chocolate ganache filling. Bambangan was incorporated into the ganache either as purée (BPG) or freeze-dried powder (FBG), and the effects of bambangan, white chocolate and cream proportions were evaluated using an extreme lattice mixture design. Texture Profile Analysis was used to evaluate the textural properties of the ganache filling, while Quantitative Descriptive Analysis was used to determine the sensory profile of the chocolate products. It was found that the processing method significantly influenced adhesiveness and all sensory attributes evaluated. Compared with BPG, FBG formulations produced chocolates with higher perceived firmness, accompanied by lower adhesiveness, smoothness, creaminess, sweetness and bitterness. BPG produced sensory characteristics most comparable to a model oil-in-water ganache, indicating that bambangan purée can be incorporated without substantially altering the sensory profile of conventional ganache-filled chocolate. Variations in bambangan, white chocolate and cream proportions exhibited different effects depending on the processing method, affecting hardness in BPG, springiness, cohesiveness and smoothness in FBG, and adhesiveness and sweetness in both systems. Principal component analysis confirmed distinct separation between chocolates formulated with bambangan purée and freeze-dried bambangan powder. The findings demonstrate that bambangan processing method influences the interactions between formulation components, textural properties and sensory characteristics in ganache systems, providing a basis for developing fruit-based chocolate products and future optimisation studies.*

Keywords: Bambangan (Mangifera pajang), dark chocolate, ganache, texture profile analysis, Sensory evaluation

INTRODUCTION

Chocolate is one of the world's most widely consumed confectionery products and is a popular platform for product innovation because of its compatibility with a diverse range of ingredients. Among chocolate products, filled chocolates continue to gain popularity as a versatile vehicle for a combination of different flavours and textures in a single product through food pairing. Ganache is one of the most common fillings used in premium chocolates because of its smooth texture, stable emulsion and ability to incorporate a wide variety of ingredients. Fruit-based ganache, in particular, has attracted increasing interest as consumers seek products with interesting flavours and added nutritional value (de Oliveira et al., 2026).

Bambangan (*Mangifera pajang* Kosterm.) is an underutilised tropical fruit native to Borneo, Brunei and Kalimantan. It is characterised by its distinctive aromatic flavour and is a good source of antioxidants and other bioactive compounds (Jahurul et al., 2019). Although bambangan is traditionally consumed fresh or processed into pickles (Ajibola et al., 2023), its application in chocolate products has received little attention. Its unique flavour profile suggests that it could complement chocolate, offering an opportunity to develop premium confectionery products using a locally available and sustainable ingredient.

Fruit purée is commonly used to introduce fruit flavour into confectionery fillings (Lapčíková et al., 2024; Panda et al., 2022). However, the high moisture content of fresh fruit can influence the stability and texture of products such as ganache. Freeze-drying has become an attractive alternative because it removes water while preserving much of the fruit's flavour, colour and bioactive compounds (Silva-Espinoza et al., 2021). At the same time, the resulting powder differs from fresh purée in its physical properties, which may influence the textural and

sensory characteristics of chocolate ganache (Ozcelik et al., 2019).

Despite the growing use of freeze-dried fruits in confectionery products, little is known about how bambangan behaves in chocolate systems. To date, no study has compared fresh bambangan purée and freeze-dried bambangan purée as ingredients in chocolate ganache or evaluated how these processing methods influence product quality. Understanding these effects is important for developing fruit-filled chocolates with desirable texture and sensory characteristics.

Therefore, this study investigated the effects of bambangan processing method (fresh purée and freeze-dried powder) and formulation on the textural and sensory properties of dark chocolate pralines filled with white chocolate ganache. The main and interaction effects of fruit, white chocolate and cream proportions were evaluated to provide insight into the role of fruit processing in determining product quality and to establish a foundation for future formulation optimisation.

MATERIALS AND METHODS

Materials

Clean, unripe Bambangan fruits were sourced from an orchard located in Babagon, Penampang, and sorted for uniform ripeness and quality. Dark couverture chocolate (minimum 60% cocoa solids) used to develop the praline shells was obtained from Marvelles Chocolates, Malaysian Cocoa Board. White chocolate callets (Callebaut), whipping cream (Anchor), unsalted butter (Anchor) and invert sugar (Trimoline) used to produce the white chocolate ganache were procured from local commercial suppliers.

Preparation and Processing of Bambangan Fruit

Bambangan fruits were left to ripen for seven days at ambient temperature before being washed, peeled, and deseeded. The pulp was sliced into small longitudinal pieces, blended (Philips 700W blender) and filtered through a 0.5 mm sieve to separate excess fibre. The yield of the resulting purée was recorded and stored at –16 °C until further use.

Bambangan purée pasteurisation

The frozen bambangan fruit purée was thawed overnight at 4 °C. The Total Soluble Solid (TSS) was measured using a digital refractometer. The purée was heated to 85 °C and held for 1 minute with continuous stirring to get a thicker consistency. The purée was immediately hot-filled into pre-sterilised Mason jars, leaving a 1-inch headspace. The sealed jars were immersed in a water bath at 88 °C for 2 minutes. The jars were then rapidly cooled in an ice bath until the internal temperature reached 40°C and were stored at 4°C (Silva & Silva, 1997.; Zalameda et al., 2016).

Bambangan purée freeze-drying

Frozen pasteurised bambangan purée samples were freeze-dried using a freeze dryer (Labconco FreeZone 6) in appropriate containers. The resulting freeze-dried pulp was blended for 20 seconds, or until a uniform powder was obtained, and then sieved through a 0.5 mm mesh to ensure particle consistency. The yield of the powder was recorded prior to packaging. The powder was then transferred into aluminium foil-laminated polyethylene pouches containing food-grade silica gel desiccants and stored under controlled conditions at 20 °C and relative humidity below 50%.

Ganache preparation

White chocolate ganache was prepared following the method of Wybauw (2008) with minor modifications. In the experimental formulations, whipping cream was partially substituted with bambangan purée or freeze-dried powder at varying concentrations established through prior studies. The proportion of white chocolate was adjusted accordingly to maintain a total ganache composition of 100%. A control sample without fruit was also prepared (Table 1). All ganache samples were allowed to cool to 30°C before further processing.

Table 1: Standard white chocolate ganache formulation

Ingredients	Content (w/w%)
White chocolate	51
Whipping cream	35
Butter	11
Invert sugar	3
Total	100

Chocolate shell preparation

Dark chocolate was melted using the bain-marie method. Two-thirds of the chocolate was poured onto a marble slab and manually tempered until it reached 29°C, following the method described by Castro-Alayo et al. (2023). The tempered chocolate was then recombined with the remaining portion in the bowl, where the final temperature is 32°C. The chocolate was poured into polycarbonate moulds and then vibrated to remove air bubbles. The surface of the moulds was scraped clean before being inverted to remove excess chocolate, leaving behind a uniform chocolate shell. The moulds were then placed in a refrigerator for at least one hour or until the chocolate was fully set.

Dark chocolate filled with ganache preparation

The ganache was piped into the moulds using a disposable piping bag, ensuring that a 2 mm gap is left to allow space for capping with chocolate. The moulds were then chilled in the refrigerator to allow the chocolate to fully set before demoulding. All samples were stored in airtight plastic containers and labelled for further analysis.

Texture Profile Analysis (TPA)

Textural properties of the ganache filling only were evaluated using a texture analyzer (TA.XTplus, Stable Micro Systems). The dark chocolate shell was excluded to avoid artificially increasing parameters such as hardness and reducing the sensitivity of TPA to differences caused by the ganache formulation. The procedure followed the method outlined by Neuwirth et al. (2024) with slight modifications. A texture profile analysis (double compression test) was carried out using a 5 mm cylindrical probe. The crosshead speed was set at 0.5 mm/s, with pre-test and post-test speeds of 2.0 mm/s and 0.5 mm/s, respectively. Samples were compressed to 25% of their height under controlled ambient conditions (20–24 °C) and the parameters of hardness, springiness, adhesiveness, and cohesiveness were measured from the resulting force-time curves. Each measurement was performed in duplicate.

Sensory Evaluation

Quantitative Descriptive Analysis (QDA) was conducted to evaluate the sensory attributes of the dark chocolate pralines. Nine trained panelists (male and female, aged 25–55 years) from the Cocoa Biotechnology Research Centre participated. Panelists were selected based on their familiarity with chocolate and bambangan products as well as their availability for the entire study. The analysis involved the evaluation of five attributes: firmness, smoothness, creaminess, sweetness, and bitterness. A structured 10-point horizontal line scale was used, with intensity increasing from left (zero) to right (ten). Two training sessions were carried out to familiarise panelists with the descriptor definition and reference samples that represent the extreme ends of the intensity scale for scoring calibration. Sensory testing was carried out in three sessions for two consecutive days. In each session, four randomly coded samples, including the blank, were served monadically according to randomized run orders to prevent order bias and learning effects. Assessments were conducted in individual sensory booths under incandescent lighting at ambient temperature (20–24 °C). Warm water was provided as a palate cleanser between samples. Table 2 summarizes the QDA attributes, definitions, and corresponding reference standards.

Table 2: Descriptors used for sensory profiling

Attribute	Definition	Reference Standards
Firmness	Force required for compressing the sample between molar teeth (Roda & Lambri, 2019)	0 = soft tofu; easily broken under very light pressure 10 = carrot; does not deform under normal chewing pressure
Smoothness	Perceived uniformity and the absence of graininess or irregularities (Ebrahimi et al., 2026)	0 = chunky peanut butter; gritty 10 = soft-serve ice cream; uniform texture with no graininess
Creaminess	The mouthfeel related to the smoothness of the chocolate as related to fat (Roda & Lambri, 2019)	0 = distilled water; thin and lacks richness 10 = clotted cream; thick and velvety
Sweetness	The taste on the tongue associated with sucrose and other sugars or sweeteners (Roda & Lambri, 2019)	0 = bambangan purée; very acidic 10 = honey; very sweet
Bitterness	The taste on the tongue associated with substances such as caffeine and quinine (Roda & Lambri, 2019)	0 = milk chocolate; not bitter 10 = Black coffee; very bitter

Statistical analysis and modelling

A three-factor Extreme Vertices Mixture design was employed to construct regression models for the responses. Tables 3 and 4 show the experimental design matrix with the proportions of the three ingredients (Bambangan fruit, cream, and white chocolate) for each run. The proportions of the three components were constrained to 86% of the total formulation, with the remaining 14% consisting of the fixed ingredients. This design allows evaluation of formulations at the boundaries of the constrained mixture space while ensuring the component proportions remain within the feasible simplex region.

Centre-point formulations, representing intermediate levels of fruit and cream, were prepared in triplicate (5th, 6th, and 7th runs) to assess model reproducibility. Data analysis was performed using pseudocomponents to minimize multicollinearity among mixture components. Model fitting was based on backward elimination of a third-degree polynomial mixture model containing linear, quadratic, and cubic terms. Regression modelling and Principal Component Analysis (PCA) were conducted using Minitab Statistical Software (Version 22) and XLSTAT, respectively. Analysis of variance (ANOVA) was used to evaluate differences among formulations, followed by Tukey's post-hoc test where significant effects were observed. An independent *t*-test was used to compare mean values between the two processing methods. Mean comparison analyses were carried out using IBM SPSS Statistics (Version 29), with statistical significance set at $p < 0.05$.

Table 3: Extreme vertices mixture design matrix for Bambangan purée ganache (BPG) formulations used as fillings in dark chocolate pralines

Formulation code	Bambangan purée (%,w/w)	White chocolate (%,w/w)	Cream (%,w/w)
BPG1	6	74	6
BPG2	29	51	6
BPG3	6	51	29
BPG4	29	28	29
BPG5	17.5	51	17.5
BPG6	17.5	51	17.5
BPG7	17.5	51	17.5
BPG8	29	40	17.5
BPG9	17.5	40	29
BPG10	17.5	62	6
BPG11	6	62	17.5

Table 4: Extreme vertices mixture design matrix for freeze-dried Bambangan ganache (FBG) formulations used as fillings in dark chocolate pralines

Formulation code	Freeze-dried bambangan powder (%,w/w)	White chocolate (%,w/w)	Cream (%,w/w)
FBG1	3	63	20
FBG2	15	51	20
FBG3	3	51	32
FBG4	15	39	32
FBG5	9	51	26
FBG6	9	51	26
FBG7	9	51	26
FBG8	3	57	26
FBG9	15	45	26
FBG10	9	57	20
FBG11	9	45	32

RESULTS AND DISCUSSIONS

Texture Profile Analysis

Ganache is a complex system that can exist as either water-in-oil or oil-in-water emulsion. Variations in relative proportions of fat and aqueous phases, the type of emulsifiers present, and the processing conditions applied can influence the structural organisation of the emulsion, thereby affecting the textural characteristics of the final product (Merachli et al., 2021). Texture Profile Analysis (TPA) is an instrumental method that purportedly evaluates these textural changes objectively. TPA enables the quantification of mechanical properties that can be related to sensory attributes perceived during oral processing (Nishinari et al., 2019). Therefore, the measured textural parameters provide valuable insights into how differences in the ingredient composition of ganache fillings influence their overall texture and consumer perception.

Table 5: Independent samples *t*-test comparing texture and sensory responses of BPG and FBG samples

Variables	Sample groups*		t (df)	p
	BPG	FBG		
Hardness	10.25 ± 12.16	18.99 ± 15.06	-1.499 (20)	0.150
Adhesiveness	10.47 ± 1.71	6.21 ± 2.66	4.464 (20)	<0.001
Springiness	0.410 ± 0.169	0.301 ± 0.106	1.820 (20)	0.084
Cohesiveness	0.301 ± 0.106	0.348 ± 0.122	-0.965 (20)	0.346
Firmness	4.53 ± 0.49	5.37 ± 0.32	-4.785 (20)	<0.001
Smoothness	8.80 ± 0.23	5.48 ± 0.19	36.708 (20)	<0.001
Creaminess	7.59 ± 0.43	6.58 ± 0.24	6.788 (20)	<0.001
Sweetness	6.88 ± 0.48	5.22 ± 0.62	6.993 (20)	<0.001
Bitterness	6.25 ± 0.38	5.84 ± 0.18	3.290 (14.44)	0.005

*Sample groups are expressed as mean ± standard deviation
df = degree of freedom

Hardness

Hardness is the maximum force recorded during the first compression cycle in a TPA test and represents the resistance of a food product to deformation (Neuwirth et al., 2024) In ganache systems, hardness is influenced by the structural integrity of the continuous and dispersed phases of the emulsion and is equivalent to the force required to penetrate the product during the first bite (McGill & Hartel, 2018). Although no significant differences in hardness were observed between the two processing methods according to the independent samples *t*-test (Table 5), significant variations were detected among formulations in each group.

Table 6: Mean values of TPA attributes for BPG samples at different formulations

Sample code	Responses[1]			
	Hardness (N)	Adhesiveness (N.s)	Springiness	Cohesiveness
Control	33.19 ± 0.82^{a}	14.75 ± 0.32^{c}	0.154 ± 0.02^{a}	0.119 ± 0.06^{a}
BPG1	44.00 ± 2.87^{a}	14.40 ± 2.76^{bc}	0.273 ± 0.05^{ab}	0.214 ± 0.03^{abc}
BPG2	11.97 ± 5.32^{bcd}	10.78 ± 0.85^{abc}	0.233 ± 0.00^{ab}	0.119 ± 0.01^{a}
BPG3	2.85 ± 0.01^{d}	7.54 ± 0.33^{a}	0.589 ± 0.09^{cd}	0.392 ± 0.06^{de}
BPG4	2.70 ± 0.24^{d}	9.75 ± 0.41^{a}	0.713 ± 0.07^{d}	0.433 ± 0.02^{e}
BPG5	4.24 ± 0.06^{cd}	10.61 ± 0.54^{ab}	0.419 ± 0.04^{bc}	0.338 ± 0.02^{cde}
BPG6	4.19 ± 0.25^{cd}	8.99 ± 1.22^{a}	0.383 ± 0.05^{b}	0.374 ± 0.03^{cde}
BPG7	4.69 ± 0.25^{cd}	10.61 ± 0.31^{ab}	0.381 ± 0.04^{b}	0.325 ± 0.01^{bcd}
BPG8	3.22 ± 0.07^{cd}	10.98 ± 0.65^{abc}	0.662 ± 0.06^{d}	0.374 ± 0.02^{de}
BPG9	5.19 ± 0.10^{cd}	9.34 ± 0.22^{a}	0.302 ± 0.06^{ab}	0.242 ± 0.03^{abc}
BPG10	16.13 ± 0.32^{b}	10.83 ± 0.30^{abc}	0.274 ± 0.02^{ab}	0.194 ± 0.01^{ab}
BPG11	13.55 ± 2.22^{bc}	11.31 ± 1.23^{abc}	0.285 ± 0.04^{ab}	0.256 ± 0.02^{abc}

[1] Values with different superscript letters in the same column are significantly different ($p<0.05$)

Table 7: Mean values of TPA attributes for FBG samples at different formulations

Sample code	Responses[1]			
	Hardness (N)	**Adhesiveness (N.s)**	**Springiness**	**Cohesiveness**
Control	33.19 ± 0.82^{f}	14.75 ± 0.32^{d}	0.154 ± 0.02^{ab}	0.119 ± 0.06^{b}
FBG1	53.30 ± 0.07^{h}	0.00 ± 0.00^{a}	0.000 ± 0.00^{a}	0.000 ± 0.00^{a}
FBG2	41.18 ± 2.44^{g}	7.00 ± 0.40^{c}	0.369 ± 0.06^{abc}	0.330 ± 0.03^{c}
FBG3	24.01 ± 1.42^{e}	9.00 ± 1.00^{c}	0.494 ± 0.31^{bc}	0.363 ± 0.05^{c}
FBG4	7.25 ± 0.64^{ab}	5.70 ± 0.22^{bc}	0.628 ± 0.15^{bc}	0.410 ± 0.04^{c}
FBG5	13.20 ± 1.57^{c}	8.49 ± 0.42^{c}	0.353 ± 0.04^{abc}	0.385 ± 0.07^{c}
FBG6	11.16 ± 0.40^{bc}	7.32 ± 0.87^{c}	0.293 ± 0.02^{abc}	0.355 ± 0.03^{c}
FBG7	12.02 ± 1.53^{c}	8.34 ± 0.16^{c}	0.355 ± 0.00^{abc}	0.376 ± 0.01^{c}
FBG8	18.24 ± 0.54^{d}	6.98 ± 0.43^{c}	0.371 ± 0.00^{abc}	0.317 ± 0.0^{bc}
FBG9	5.82 ± 0.26^{a}	5.65 ± 2.57^{bc}	0.710 ± 0.29^{bc}	0.430 ± 0.02^{c}
FBG10	12.25 ± 1.26^{c}	2.86 ± 0.50^{ab}	0.655 ± 0.07^{bc}	0.423 ± 0.02^{c}
FBG11	10.49 ± 0.85^{abc}	6.95 ± 0.70^{c}	0.789 ± 0.27^{c}	0.440 ± 0.02^{c}

[1] Values with different superscript letters in the same column are significantly different ($p<0.05$)

As shown in Tables 6 and 7, ganache formulations containing BPG exhibited hardness values ranging from 3 to 44 N, whereas formulations prepared with FBG ranged from 6 to 53 N.

Table 8: Model statistics of significant regression models for BPG response variables

Response	Model p-value	R^2	Adjusted R^2	Lack-of-fit (p-value)
Hardness	<0.001	0.9796	0.9694	0.103
Adhesive-ness	<0.001	0.8488	0.7858	0.407
Sweet-ness	0.002	0.8264	0.7520	0.962

Table 9: Regression coefficients of significant model terms of texture and sensory attributes for BPG samples

Response	Model term	p-value	Coefficient value
Hardness	A×B	<0.001	-152.8
	A×C	<0.001	-208.6
	B×C	<0.001	-189.2
	A×B×C	<0.001	320.7
Adhesiveness	A	<0.001	10.1
	B	<0.001	11.2
	C	<0.001	-0.5
	A×C	0.001	21.0
	B×C	0.035	10.0
Sweetness	A	0.002	5.2
	B	0.002	7.5
	C	0.002	7.4

Terms; A: Bambangan purée; B: White chocolate; C: Cream

Regression analysis indicates that only the BPG model is significantly affected by the formulation variables, whereby variations in bambangan fruit concentration, white chocolate and cream significantly influenced ganache hardness (Tables 8 and 9). Within the BPG samples, firmer formulations (BPG1, BPG10 and BPG11) were generally associated with higher proportions of white chocolate concentrations (62–74%), while the softest formulation contained the highest proportions of Bambangan purée and cream. The non-significant main effects suggest that hardness is not governed by individual ingredients alone, but rather by their combined interactions within the system. Interaction analysis revealed that all binary interactions between Bambangan purée, white chocolate, and cream had a negative effect on hardness in the BPG system. The softening effect associated with higher levels of fruit purée is consistent with the findings by Neuwirth et al. (2024). They attributed this effect to the reduction in dairy proteins available to bind water as cream was replaced with the fruit purée.

Furthermore, the fat composition of cream and white chocolate also plays a key role in structuring the ganache matrix. When the proportion of milk fat from cream and cocoa butter exceeds 30% of the fat phase, a eutectic effect occurs, which significantly lowers the melting point and softening the fat network (McGill & Hartel, 2018). Reducing cream content may

therefore decrease the amount of milk fat available to disrupt cocoa butter crystallisation, allowing a more rigid structure to form (Hřivna et al., 2021). This structural rigidity is further enhanced at higher white chocolate concentrations, where the high solid fat content of cocoa butter increases the proportion of crystalline fat droplets in the dispersed phase, ultimately creating a denser and firmer ganache (Saglio et al., 2018). Similar increases in chocolate ganache hardness were reported by Kim et al. (2017) when low-fat vegetable cream was substituted for whipped cream. Guinard & Mazzucchelli (1999) also highlighted an antagonistic relationship between fat and sugar matrices that significantly influences overall structural hardness.

Interestingly, the three-way interaction between Bambangan purée, white chocolate, and cream exerted an opposing effect, suggesting a synergistic balance between components that enhances structural resistance when properly proportioned. Overall, the BPG regression model demonstrated strong goodness-of-fit, with high determination coefficient (R^2 = 97.96%) and adjusted coefficient (R^2 = 96.64%) values. The results highlight the importance of the relative balance of ingredients in determining ganache hardness.

Adhesiveness

Adhesiveness [N (force) × s (time)] is defined as the work required to overcome attractive forces between the ganache surface and the probe during its withdrawal after the first compression cycle, calculated as the negative area under the force–time curve (Neuwirth et al., 2024). In sensory terms, it reflects the stickiness of the ganache against the palate, tongue or teeth during mastication (Lavrenova et al., 2023). The independent samples *t*-test revealed significant differences in mean adhesiveness between processing methods ($p<0.001$) (Table 5), with samples prepared with BPG exhibiting significantly higher adhesive strength (7.31–14.75 N·s) than those prepared with FBG (0–9.71 N·s). Furthermore, significant variations were also detected among formulations within each treatment group (Tables 6 and 7).

Table 10: Model statistics of significant regression models of texture and sensory attributes for FBG samples

Response	Model p-value	R^2	Adjusted R^2	Lack-of-fit (p-value)
Adhesiveness	<0.001	0.9453	0.9343	0.346
Springiness	<0.001	0.7631	0.7157	0.472
Cohesiveness	<0.001	0.9335	0.9203	0.200
Sweetness	<0.001	0.8796	0.8495	0.876
Smoothness	0.005	0.9238	0.8628	0.731

Table 11: Regression coefficients of significant model terms of texture and sensory attributes for FBG samples

Response	Model term	p-value	Coefficient
Adhesiveness	A	<0.001	13.4
	B	<0.001	0.1
	C	<0.001	-2.5
	B×C	<0.001	41.2
Springiness	A	<0.001	0.7
	B	<0.001	-0.04
	C	<0.001	1.5
	A×C	0.031	-1.8
Cohesiveness	A	<0.001	0.66
	B	<0.001	0.009
	C	<0.001	0.17
	B×C	<0.001	1.3
Sweetness	A	<0.001	3.1
	B	<0.001	6.1
	C	<0.001	5.6
Smoothness	A	0.003	6.5
	B	0.003	5.8
	C	0.003	4.1
	A×B	0.004	-3.1
	B×C	0.015	2.2

Terms; A: Bambangan freeze-dried powder; B: White chocolate; C: Cream

Regression analysis identified that both models for adhesiveness were significant, with linear and quadratic terms contributing to the response (Tables 8 and 10). Specifically, fruit and white chocolate exerted a positive effect on the adhesiveness, whereas cream had a negative, moderating effect (Table 11). Across both low and high fruit concentrations, formulations with higher cream proportions consistently exhibited lower stickiness, indicating that cream acts as a lubricating phase that moderates the adhesive contribution of white chocolate

and fruit. This crossover behavior highlights the importance of balancing cream content against solid ingredients to achieve the desired textural mouthfeel.

The structural relationship between hardness and adhesiveness differed substantially between the two processing methods. In the BPG system, harder formulations generally exhibited higher adhesive strength, driven by strong inter-particle interactions, where finer particle size distributions reduce particle mobility and produce a denser structure with greater surface stickiness (Fibrianto et al., 2021; Indiarto et al. , 2021).

Conversely, no clear relationship between hardness and adhesiveness was observed in the FBG system. Notably, the firmest formulation (FBG1) recorded zero instrumental adhesiveness because the sample fractured during initial compression. As explained by Nishinari et al. (2019), samples that crumble or break upon initial impact fail to maintain contact with the probe withdrawal, resulting in a complete absence of measurable attractive forces.

Overall, variation in ingredient composition explained adhesiveness more effectively in the FBG system (R^2 = 94.53%, adjusted R^2 = 92.03%) than in the BPG system (R^2 = 78.90%, adjusted R^2 = 66.5%). Despite the moderate explanatory power of the BPG model, these findings provide a noteworthy contribution to confectionery science, as Neuwirth et al. (2024) previously reported no significant differences in adhesiveness among ganache formulations containing raspberry purée.

Springiness and Cohesiveness

Springiness represents a sample's ability to recover its original shape after deformation during the first compression cycle whereas cohesiveness reflects the internal strength of the ganache matrix and the extent to which it can deform before rupture (Aguirre et al., 2018). According to Jonkers et al. (2022), these two parameters are fundamentally linked because they both describe the deformation behaviour of a material during compression. The two parameters began to differ only when structural damage occurs, with cohesiveness becoming sensitive to the damage while springiness continues to reflect the deformation, which may be recoverable (viscoelastic) or irrecoverable (plastic). For this reason, both parameters are discussed together.

Springiness values ranged from 0.23 to 0.60 for the BPG formulations and from 0.00 to 0.71 for the FBG formulations, while cohesiveness ranged from 0.11 to 0.44 and 0.00 to 0.41, respectively (Tables 6 and 7). No significant differences were observed between the two processing methods ($p > 0.05$), indicating that the form of Bambangan used did not influence either textural property (Table 5). However, significant differences among formulations were detected within both treatment groups ($p<0.05$), with regression analysis showing that only the FBG models were significantly affected by formulation variables (Table 10). According to McGill & Hartel (2018), ganache tends to be more elastic than viscous at low deformation rates near room temperature, thus producing some level of recoverable springiness. However, as deformation increases, the internal network begins to break down due to weak structural bonds. In this study, the firmest FBG formulation (FBG1) fractured during the initial compression cycle, generating zero values for both parameters and demonstrating that over strengthening of the matrix result in brittle fracture instead of elastic recovery.

Regression coefficients showed that all three formulation variables were positive contributors to both parameters, except for the individual effect of white chocolate on springiness (Table 11). The high solid fat content of white chocolate creates a denser fat crystal network where stronger interparticle forces increase structural cohesion but decrease elastic recovery (Indiarto et al., 2021). A similar relationship was found between hardness and springiness, where formulations with greater hardness typically demonstrated lower springiness. Nevertheless, there was no consistent pattern observed between cohesiveness and hardness across formulations, suggesting that the internal strength of a ganache network is determined not just by firmness but also by the types of interactions among the formulation components.

Regarding interaction effects, springiness in the FBG system was significantly influenced by the interaction between FDP and cream. High water absorption by FDP reduces free water mobility in the

aqueous cream phase, which together with the solid fat content contributed by white chocolate, promotes a more constrained matrix that limits elastic recovery (Gheorghe et al., 2026). Meanwhile, cohesiveness was affected by the interaction between white chocolate and cream, indicating that internal structure integrity depends heavily on their combined ratio rather than individual components. Notably, formulation FBG8 exhibited cohesiveness comparable to the control, likely due to its balanced proportions of white chocolate, cream, and low FDP content.

Overall, the springiness model demonstrated moderate predictive ability, with R^2 and adjusted R^2 values of 76.31% and 71.57%, respectively. In contrast, the cohesiveness model performed considerably better, with corresponding R^2 and adjusted R^2 values of 93.35% and 92.03%.

Sensory Evaluation

Quantitative Descriptive Analysis (QDA) was conducted to develop a sensory profile of the chocolate samples and evaluate the influence of formulation variables on sensory perception. The fruit processing method significantly influenced the sensory characteristics of the chocolates. Overall, the FBG samples were perceived as firmer than the BPG samples, while scoring lower for the remaining sensory attributes ($p < 0.05$).

Meanwhile, varying the proportions of fruit, white chocolate and cream had little effect on most sensory attributes in both groups, except for creaminess in the BPG formulations and sweetness in the FBG formulations. Among the BPG samples, BPG1 was perceived as less creamy than BPG9, whereas BPG9 was comparable to the control. In the FBG system, FBG8 was significantly sweeter than FBG4 and FBG9. Regression analysis further showed that only two of the five sensory attributes, sweetness and smoothness, were significantly affected by formulation variables.

Table 12: Mean values of QDA sensory attributes for BPG samples at different formulations

Sample code	Responses[1]				
	Firmness	**Sweetness**	**Smoothness**	**Creaminess**	**Bitterness**
Control	3.89 ± 0.78^{a}	7.33 ± 0.87^{a}	9.44 ± 0.73^{a}	8.22 ± 0.67^{b}	5.78 ± 1.79^{a}
BPG1	4.44 ± 1.13^{a}	7.67 ± 1.01^{a}	8.78 ± 1.64^{a}	6.56 ± 1.0^{a}	5.67 ± 1.80^{a}
BPG2	3.89 ± 0.60^{a}	6.44 ± 0.73^{a}	9.00 ± 1.32^{a}	7.78 ± 0.44^{ab}	6.00 ± 1.58^{a}
BPG3	4.89 ± 1.36^{a}	7.44 ± 1.24^{a}	8.78 ± 1.99^{a}	7.44 ± 1.24^{ab}	6.56 ± 1.01^{a}
BPG4	4.22 ± 1.09^{a}	6.44 ± 1.27^{a}	8.67 ± 2.24^{a}	7.67 ± 1.12^{ab}	6.67 ± 1.41^{a}
BPG5	5.00 ± 1.66^{a}	6.89 ± 0.71^{a}	8.56 ± 2.01^{a}	7.56 ± 0.88^{ab}	6.33 ± 1.66^{a}
BPG6	4.44 ± 0.73^{a}	7.33 ± 0.71^{a}	8.44 ± 2.01^{a}	7.89 ± 0.78^{ab}	6.67 ± 0.71^{a}
BPG7	4.00 ± 0.71^{a}	6.67 ± 1.17^{a}	8.67 ± 1.87^{a}	7.33 ± 0.71^{ab}	5.89 ± 1.54^{a}
BPG8	5.00 ± 1.32^{a}	6.11 ± 1.12^{a}	8.78 ± 1.30^{a}	7.56 ± 0.53^{ab}	5.89 ± 2.52^{a}
BPG9	4.44 ± 1.13^{a}	6.67 ± 0.97^{a}	9.22 ± 0.83^{a}	8.33 ± 1.00^{b}	6.22 ± 1.64^{a}
BPG10	5.44 ± 1.74^{a}	6.78 ± 1.30^{a}	9.11 ± 0.78^{a}	7.67 ± 1.00^{ab}	6.78 ± 1.30^{a}
BPG11	4.11 ± 0.60^{a}	7.22 ± 1.23^{a}	8.78 ± 1.20^{a}	7.67 ± 1.32^{ab}	6.11 ± 1.27^{a}

[1] Values with different superscript letters in the same column are significantly different ($p<0.05$)

Table 13: Mean values of QDA sensory attributes for FBG samples at different formulations

Sample code	Responses[1]				
	Firmness	**Sweetness**	**Smoothness**	**Creaminess**	**Bitterness**
Control	3.89 ± 0.78^{a}	7.33 ± 1.23^{c}	9.44 ± 0.73^{b}	8.22 ± 0.67^{b}	5.78 ± 1.79^{a}
FBG1	5.33 ± 0.71^{b}	5.78 ± 0.97^{abc}	5.78 ± 0.83^{a}	6.67 ± 0.71^{a}	5.78 ± 0.44^{a}
FBG2	5.56 ± 1.01^{b}	4.78 ± 1.09^{ab}	5.33 ± 0.87^{a}	6.44 ± 0.53^{a}	6.00 ± 1.12^{a}
FBG3	5.44 ± 0.88^{b}	5.89 ± 0.78^{abc}	5.44 ± 1.01^{a}	6.89 ± 0.78^{ab}	5.89 ± 1.05^{a}
FBG4	5.11 ± 0.60^{b}	4.33 ± 1.12^{a}	5.33 ± 0.50^{a}	6.22 ± 0.67^{a}	5.89 ± 1.27^{a}
FBG5	5.44 ± 0.73^{b}	5.33 ± 0.87^{ab}	5.67 ± 0.71^{a}	6.78 ± 0.67^{a}	5.78 ± 0.44^{a}
FBG6	5.56 ± 0.88^{b}	5.56 ± 1.01^{ab}	5.44 ± 0.73^{a}	6.78 ± 0.67^{a}	6.00 ± 0.71^{a}
FBG7	5.22 ± 0.83^{b}	4.89 ± 0.78^{ab}	5.56 ± 1.42^{a}	6.89 ± 0.78^{ab}	6.11 ± 0.60^{a}
FBG8	5.00 ± 0.50^{ab}	6.11 ± 1.27^{bc}	5.78 ± 1.39^{a}	6.44 ± 1.01^{a}	5.44 ± 1.81^{a}
FBG9	5.00 ± 0.50^{ab}	4.22 ± 1.72^{a}	5.44 ± 1.51^{a}	6.44 ± 1.24^{a}	5.78 ± 2.11^{a}
FBG10	6.11 ± 0.60^{b}	5.44 ± 1.13^{ab}	5.33 ± 1.58^{a}	6.56 ± 1.33^{a}	5.67 ± 1.32^{a}
FBG11	5.33 ± 0.50^{b}	5.11 ± 0.93^{ab}	5.22 ± 0.67^{a}	6.22 ± 0.67^{a}	5.89 ± 0.60^{a}

[1] Values with different superscript letters in the same column are significantly different ($p<0.05$)

Sweetness

The control ganache recorded the highest sweetness score (7.33). ANOVA showed no significant differences between the BPG samples and the control, suggesting that bambangan purée inclusion did not perceptibly alter sweetness intensity. In contrast, the inclusion of freeze-dried bambangan produced ganache with significantly lower sweetness than the control and the purée-based formulations, except for samples containing the lowest concentration of FDP, which were similar to the control (Tables 12 and 13).

Regression analysis showed that all three ingredients contributed positively to sweetness in both processing systems. The models explained the response well, with R^2 values of 82.64% (BPG) and 87.96% (FBG), and adjusted R^2 values of 75.20% and 84.95%, respectively. Although FDP had a positive pseudocomponent coefficient, its contribution was considerably smaller than those of white chocolate and cream (Table 11). Accordingly, increasing the proportion of FDP while reducing white chocolate and cream decreased the predicted sweetness, as demonstrated by the contour plot (not shown).

The lower sweetness of the FBG formulations is related to changes in the ratio of total soluble solids to titratable acidity (TSS/TA), which is used as an indicator of perceived sweetness as it reflects the balance between sugars and organic acids. In sensory perception, organic acids that impart sourness tend to have a strong influence on taste, where increased sourness can mask or reduce the perception of sweetness. Depending on their concentration and composition, organic acids may also enhance sweetness perception (Ikegaya, 2024). Bambangan pulp contains ascorbic acid at levels comparable to common mango, along with various phenolic acids (Jahurul et al., 2019). During freeze-drying, the removal of moisture likely concentrated these organic acids, which intensified sourness and subsequently reduced perceived sweetness.

In addition, cream aroma, which increases with milk fat content in chocolate, can enhance sweetness perception through cross-modal interactions. Cross-modal interactions refer to interactions between different sensory modalities such as taste and smell or texture and taste (Pedersen et al., 2023).

These findings suggest that the sweetness of bambangan-filled chocolate ganache can be controlled primarily through adjustment of white chocolate, fruit and cream concentrations. The relatively lower sweetness of FBG samples may be advantageous for developing premium dark chocolate products aimed at consumers who prefer less sweet and more flavour-intense confectionery. Similar trends have been reported in chocolates containing freeze-dried fruit, where these products exhibit stronger fruit flavour and lower perceived sweetness compared to other variants (Augusto et al., 2019).

Smoothness

Smoothness is an important mouthfeel attribute that describes the perceived uniformity of a sample and the absence of graininess during mastication (Ebrahimi et al., 2026). ANOVA showed that only the FBG formulations differed significantly from the control ($p < 0.05$), whereas no significant differences were observed between the BPG formulations and the control (Tables 12 and 13). Likewise, regression analysis identified significant formulation effects only in the FBG system. The model explained the response well, with an R^2 value of 92.38% and an adjusted R^2 of 86.28%.

The interactions between white chocolate and freeze-dried powder, as well as white chocolate and cream were the dominant factors influencing this attribute, with both interactions exhibiting curvilinear response surfaces (not shown).

The smoothest texture was obtained at high white chocolate concentrations combined with low levels of FDP. Although FDP showed a positive linear effect, its negative interaction with white chocolate indicates that their combined effect reduced smoothness compared with their individual contributions. At higher concentrations, the freeze-dried powder appeared to disrupt the continuous fat matrix formed by the white chocolate, resulting in a rougher mouthfeel.

This reduction in smoothness may be attributed to the physical properties of the powder. The surface of FDP is highly porous and irregular, with various degrees of ridges and concavities (Preciado Ocampo et al., 2025). As powder concentration increases, the particles become more noticeable during mastication. The resulting increase in particulate size contributes to a coarser or grainier mouthfeel and lower smoothness ratings (Gheorghe et al., 2026). Augusto et al. (2019) found that high lipid-containing FDP such as those derived from açaí, can improve smoothness because the retained lipids provide additional lubrication. Bambangan, however, contains relatively little fat which likely explains its negative effect on smoothness at higher levels.

The curvilinear interaction between white chocolate and cream indicates that moderate levels of both ingredients enhanced smoothness, whereas higher concentrations led to a decline. White chocolate and cream contain milk fat which provides the fat phase of the ganache along with non-uniform fat globules that function as lubricants in the multi-phase system. These larger fat globules increase distance between suspended solids such as sugar, reducing particle-to-particle contact and creating a softer, smoother mouthfeel (McGill & Hartel, 2018).

Based upon these results, bambangan can be effectively incorporated in purée form without noticeably affecting smoothness. In contrast, using FDP requires careful adjustment of the balance between fruit, white chocolate, and cream, to achieve the desired mouthfeel. Since smoothness is critical for consumer acceptance of chocolate products containing dehydrated fruit ingredients (Augusto et al., 2019), controlling this attribute will be essential for developing bambangan-filled chocolate ganache.

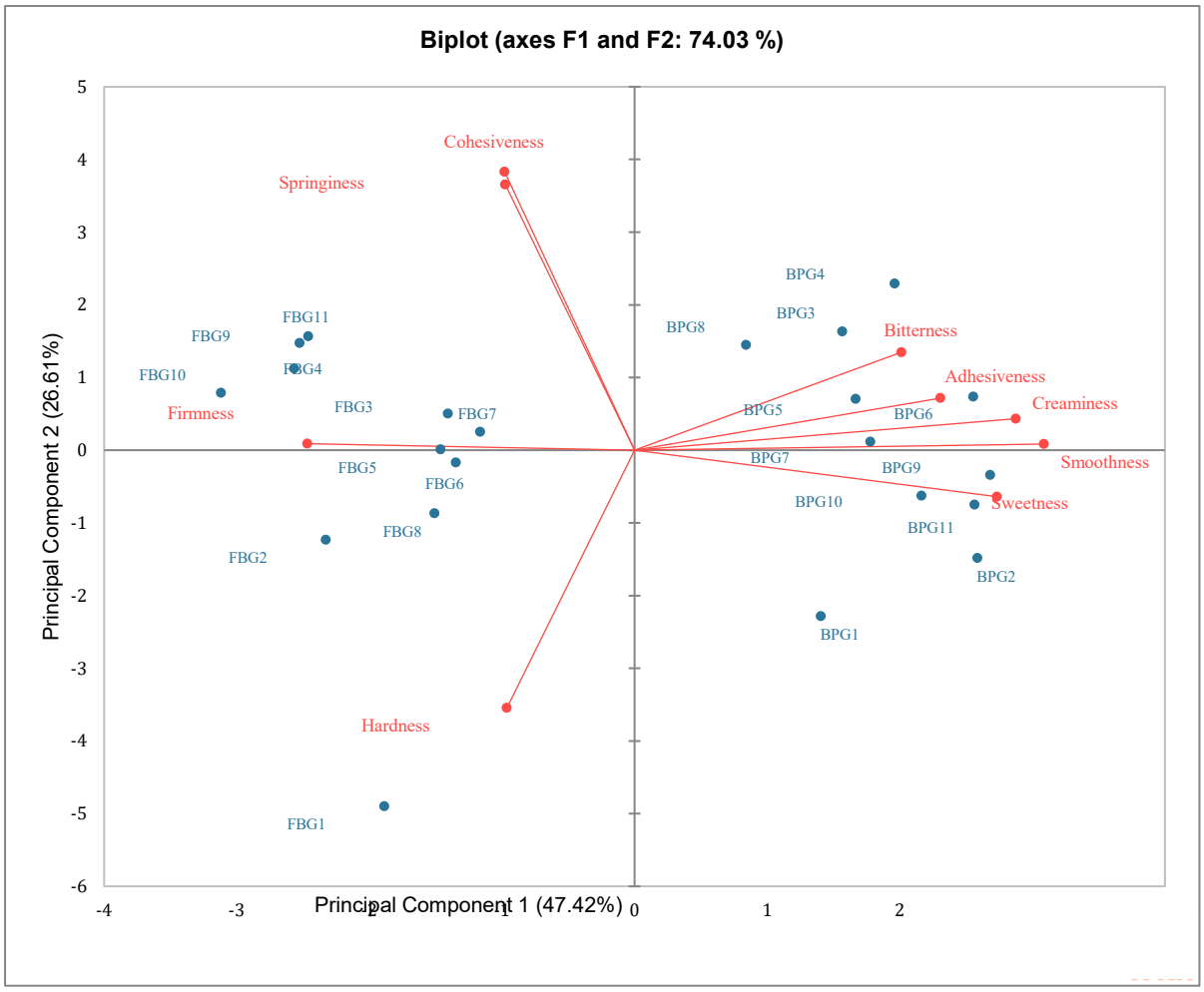


Figure 1: PCA biplot showing the distribution of dark chocolate samples containing bambangan ganache with different processing methods and concentrations relative to their texture and sensory attributes

Principal Component Analysis

The Principal Component Analysis (PCA) biplot in Figure 1 clearly demonstrates a distinct separation between formulations created using fresh purée (BPG) and freeze-dried purée (FBG). Samples clustered close together exhibit similar attribute profiles, and variables positioned near one another indicate positive correlation. Meanwhile, the vector orientation illustrates the attribute's influence on the principal components. BPG samples were positioned on the positive side of the principal component 1 (PC1) axis and were generally associated with sensory attributes such as sweetness, creaminess, smoothness, adhesiveness, and bitterness. In contrast, FBG samples were located on the principal component 2 (PC2) axis and were more closely associated with hardness, cohesiveness, springiness, and firmness. PC1 (47.42%) and PC2 (26.61%) together accounted for 74.03% of the total variance, indicating that the PCA model adequately represented the major sources of variation among the formulations. Overall, these findings demonstrate that the influence of Bambangan concentration and processing methods on texture and sensory characteristics of ganache-filled chocolate differs substantially between fresh purée and freeze-dried purée.

CONCLUSIONS

The application of Bambangan purée (BPG) and freeze-dried powder (FBG) distinctly influenced the textural and sensory properties of white chocolate ganache-filled dark chocolate. Overall, BPG formulations were perceived as softer, with sensory attributes of firmness, sweetness and smoothness closely resembling those of the control sample. Conversely, FBG formulations were perceived as firmer and exerted a more pronounced effect on certain sensory attributes, notably reducing perceived sweetness and smoothness. Furthermore, the two-way and three-way interaction models demonstrated that ingredient proportions (white chocolate, cream and fruit) must be precisely balanced to avoid undesirable structural defects, such as brittle fracturing or loss of smoothness. Principal Component Analysis (PCA) successfully explained 74.03% of the total variance, confirming a clear separation between fresh purée and freeze-dried powder applications. These findings indicate that fresh purée is better suited for maintaining traditional, smooth ganache characteristics, whereas freeze-dried powder offers a viable approach for tailoring firmer textures and unique flavour profiles in premium chocolate products. Future studies should focus on formulation optimisation as well as shelf-life stability and consumer acceptance to support their potential commercial application.

Differences between processing methods were generally insignificant, except for adhesiveness. Freeze-dried Bambangan exerted a more pronounced effect on most sensory attributes, with the exception of bitterness of the dark chocolate. In contrast, BPG formulations were generally more comparable to the control samples. The impact of Bambangan was also dependent on the relative proportions of cream and white chocolate. These formulation differences led to variations in hardness, adhesiveness, and sensory attributes such as sweetness and smoothness. Additional differences were observed in springiness and cohesiveness in the FBG system. These findings highlight the potential of Bambangan fruit as a functional ingredient in chocolate ganache, where its application can be tailored through processing methods and ingredient proportions to achieve desired product characteristics.

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