VITAE

ORIGINAL ARTICLE
Published 23 December 2025
DOI: https://doi.org/10.17533/udea.vitae.v32n3a362099

Incorporation of Solar-Dried Plantain Flour in Cookies: Balancing Nutrition, Acceptability, and Sustainability

Incorporación de harina de plátano secada al sol en galletas: equilibrio entre nutrición, aceptabilidad y sostenibilidad

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JOURNAL VITAE
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ISSN 0121-4004 | ISSNe 2145-2660
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Received: 1 September 2025
Accepted: 19 December 2025
Published: 23 December 2025

How to cite: Fajardo-Ariza, T., Nieto-Veloza, A., & Zuluaga Domínguez, C. M. (2025). Incorporation of Solar-Dried Plantain Flour in Cookies: Balancing Nutrition, Acceptability, and Sustainability. *Vitae, 32*(3). https://doi.org/10.17533/udea.vitae.v32n3a362099

ABSTRACT

Background: Post-harvest losses and nutritional deficiencies remain significant challenges in food production, requiring innovative strategies for sustainable ingredient utilization. Solar drying offers a low-cost and eco-friendly method to extend the shelf life of perishable foods, such as plantain, while supporting functional food development. **Objectives**: This study aimed to evaluate the impact of incorporating solar-dried plantain flour as a potential replacement for wheat flour in cookies, focusing on nutritional enhancement, sensory acceptability, and sustainability. **Methods**: Cookies were prepared with four substitution levels of plantain flour (0%, 50%, 75%, and 100%). Physicochemical, structural, and sensory properties were assessed, and a combination of Principal Component Analysis (PCA) and the Total Order Ranking Test was applied to identify the optimal formulation. **Results**: Higher substitution with plantain flour increased dietary fiber content but decreased protein levels and reduced Maillard reaction-driven browning, influencing texture and color. Among the formulations, the 50% wheat–50% plantain flour blend (T50P50) provided the best balance of nutritional quality, texture, flavor, and consumer acceptance. **Conclusions**: Solar-dried plantain flour is a viable functional ingredient for cookie production, offering nutritional and sustainability benefits while reducing post-harvest losses. The use of solar drying demonstrates potential as an accessible, eco-friendly processing technique. Future research should explore strategies to enhance protein content, optimize sensory attributes, and extend applications of plantain flour in bakery and gluten-free products for broader market adoption.

Keywords: cookie formulation, solar drying, plantain flour, nutritional quality, wheat flour replacement

RESUMEN

Antecedentes: Las pérdidas postcosecha y las deficiencias nutricionales siguen siendo desafíos significativos en la producción de alimentos, lo que exige estrategias innovadoras para el aprovechamiento sostenible de ingredientes. El secado solar es un método de bajo costo y ecológico para prolongar la vida útil de alimentos perecederos, como el plátano, al tiempo que respalda el desarrollo de alimentos funcionales. **Objetivo**: Evaluar el impacto de la incorporación de harina de plátano secada al sol como posible sustituto de la harina de trigo en galletas, centrándose en el mejoramiento nutricional, la aceptabilidad sensorial y la sostenibilidad. **Métodos:** Se prepararon galletas con cuatro niveles de sustitución de la harina de plátano (0 %, 50 %, 75 % y 100 %). Se evaluaron las propiedades fisicoquímicas, estructurales y sensoriales, y se aplicó una combinación de Análisis de Componentes Principales (ACP) y la Prueba de Ordenamiento Total para identificar la formulación óptima. **Resultados:** Una mayor sustitución con harina de plátano incrementó el contenido de fibra dietaria, pero disminuyó los niveles de proteína y redujo el pardeamiento inducido por la reacción de Maillard, lo que influyó en la textura y el color. Entre las formulaciones, la mezcla 50 % trigo–50 % harina de plátano (T50P50) proporcionó el mejor equilibrio entre la calidad nutricional, la textura, el sabor y la aceptación del consumidor.**Conclusiones:** La harina de plátano secada al sol es un ingrediente funcional viable para la producción de galletas, ya que ofrece beneficios nutricionales y de sostenibilidad, además de reducir las pérdidas postcosecha. El uso del secado solar demuestra su potencial como una técnica de procesamiento accesible y ecológica. Investigaciones futuras deberían explorar estrategias para aumentar el contenido proteico, optimizar los atributos sensoriales y ampliar las aplicaciones de la harina de plátano en productos de panadería y sin gluten, para una mayor adopción en el mercado.

Palabras clave: formulación de galletas, secado solar, harina de plátano, calidad nutricional, sustitución de harina de trigo

1. INTRODUCTION

Food loss, particularly of fruits and vegetables, is a major global challenge, with estimates ranging between 30% and 50% of total production [1]. These reductions in food availability occur at various stages of the food supply chain, from harvest to retail, primarily due to inadequate infrastructure for processing and marketing, logistical challenges, and high transportation costs [2,3]. This poses a threat to efforts made at reducing the growing global hunger crisis. According to the FAO's 2021 SOFI report, 828 million people worldwide are affected by hunger—an increase of 46 million people compared to 2020 and 150 million compared to 2019. Furthermore, about 3.1 billion people lack access to a healthy diet, underscoring the scale of the global food security challenge [4]. The magnitude of food wastage contributes directly to these alarming statistics. The FAO's 2019 report estimates that 14% of global food production, valued at $400 billion annually, is lost post-harvest but before reaching retailers. Additionally, UNEP's Food Waste Index reveals that 17% of food is discarded at the retail and household levels. Collectively, these inefficiencies could potentially feed up to 1.26 billion people each year, highlighting the critical need for improved food system efficiency [4].

Perishable foods, such as fruits and vegetables, are especially vulnerable to post-harvest losses due to their short shelf life, high moisture content, and the logistical difficulties associated with harvesting, handling, and transportation [3]. In many tropical and subtropical regions, these challenges are exacerbated by inadequate cold-chain infrastructure, limited access to appropriate storage technologies, and fluctuating climatic conditions that accelerate microbial spoilage and physiological deterioration. Additional factors include poor road connectivity, lack of processing facilities near production areas, and insufficient technical training for farmers, increasing the likelihood of losses during collection, sorting, and distribution. In consequence, post-harvest losses reduce the volume of marketable produce, leading to lower household incomes and heightened economic vulnerability among smallholder farmers. At a broader level, these losses diminish local food availability, undermine the resilience of food systems, and threaten cultural practices linked to traditional crops [5,6].

One promising approach to reduce post-harvest losses is the transformation of perishable foods into stable, nutrient-rich ingredients. Plantain (*Musa paradisiaca*) is a staple food which serve as a major source of carbohydrates for millions of people in Africa, the Caribbean, Latin America, Asia, and the Pacific [7,8]. Plantains are rich in essential nutrients, including dietary fiber, vitamins, minerals, and polyphenols, contain high levels of resistant starch, which has been shown to offer a variety of health benefits, such as improved blood sugar control and enhanced gut health [5,6,9–11]. However, poor post-harvest practices force producers to use surplus production for internal consumption, animal feed, or organic fertilizers, thereby missing economic opportunities.

Dehydration is one of the most common method to reduce water content, being useful to extend the shelf life of perishable foods by reducing their water activity, slowing spoilage processes, and preventing microbial growth [3,12,13]. This process, achieved through heat and mass transfer mechanisms, typically involves temperatures generally from 40°C up to 70°C or higher, depending on the drying technique used (e.g., solar drying, hot-air drying, fluid-bed drying, or freeze-drying), to ensure safety and quality [14]. Beyond extending shelf life, dehydration adds value by reducing product weight and volume, facilitating transport and storage, and preserving essential nutrients and flavors. This is especially beneficial in rural areas facing food security and market access challenges [15].

Solar drying, in particular, is an ideal preservation method for tropical crops like plantains. It uses renewable solar energy, is environmentally friendly, cost-effective, and accessible to resource-limited communities [16]. Although advanced thermal techniques such as spray drying and convective hot-air drying can provide improved control over processing conditions, freeze-drying, a low-temperature, non-thermal dehydration method, is widely recognized for its superior preservation of sensory, nutritional, and functional attributes. However, all these technologies require high energy inputs, specialized equipment, and elevated operational costs, which limit their applicability in resource-constrained settings. [14,17,18]. Consequently, these methods are often difficult for smallholder farmers or rural processors to access due to their high capital, energy, and operational requirements. Although solar drying presents limitations, including dependence on weather conditions, longer drying times, and potential variability in temperature and airflow that may affect product quality [19], it also remains a viable and sustainable option for producing plantain flour in regions with abundant sunlight, as it enables value addition, reduces post-harvest losses, and supports local food security.

Although wheat flour is a staple ingredient in baked goods, there is increasing global interest in alternative flours that cater to the demand for healthier, more nutritious products while addressing sustainability challenges. Dehydrated plantains can be processed into gluten-free flour rich in dietary fiber, resistant starch, and essential minerals like potassium, offering significant nutritional benefits [20]. Incorporating plantain flour into cookies helps address global dietary fiber deficiencies, as the average intake in many countries falls far below the recommended levels of 25-30 g per day for adults [21,22]. Cookies, being widely consumed and shelf-stable, serve as an ideal platform for incorporating plantain flour without compromising sensory appeal or economic feasibility. This aligns with the growing demand for functional foods and plant-based, nutrient-dense snacks, positioning plantain flour as a valuable ingredient for promoting healthier eating, reducing food waste, and supporting local agricultural economies [11,23].

In consequence, this study aimed to evaluate the use of solar-dried plantain flour as an alternative to wheat flour in cookie production. Specifically, the research assessed the impact of substituting plantain flour on the physicochemical, textural, and sensory properties of cookies while considering sustainability aspects. Previous research has extensively studied the replacement of wheat flour with plantain flour in cookies, yet few studies have systematically analyzed the impact of solar drying as a processing method.

Unlike prior works that employed oven-dried or freeze-dried plantain flour [6,11], this study highlights the sustainability benefits of solar drying. It provides specific drying parameters that influence final product characteristics. Additionally, while several studies have explored sensory properties of wheat-plantain cookies, the application of Principal Component Analysis (PCA) and the Total Order Ranking Test in this research offers a novel, data-driven approach to optimizing formulation decisions based on both nutritional and sensory factors. This research is particularly relevant for regions where wheat flour is scarce or expensive, as adopting locally sourced plantain flour can strengthen rural economies, reduce dependency on imported ingredients, and offer healthier food options. Beyond cookies, solar-dried plantain flour has potential applications in bread, cakes, gluten-free products, snack production, and as a thickening agent for soups and sauces. These applications contribute to sustainable food innovation while addressing dietary and economic needs in both local and global markets.

2. MATERIALS AND METHODS

2.1 Materials

Unripe plantains were provided by the Association of Farmers and Beekeepers from Serranía de los Yariguíes – APISY, located in Galan, Santander, Colombia. The rest of materials used for the elaboration of cookies were purchased in a local market in Bogotá, Colombia: Wheat flour (Haz de Oros®), Oatmeal flour (Quaker®), Cassava starch (Maizena®), Margarine (La Fina®), Refined sugar (Incauca®), Unrefined whole cane sugar (Alkosto®), Whole milk (Colanta®), Eggs (Santa Anita®), Honey (Alkosto®), Cinnamon powder (El Rey®), Baking soda (Levapan®), and Vanilla essence (Levapan®). Materials were stored at room temperature (23 °C ± 2°C) until use, except for margarine, which was refrigerated at 5 °C ± 2°C.

2.2. Production of plantain flour

To produce plantain flour, 10 kg of unripe plantains were peeled and manually sliced into 3-5 mm-thick pieces. The slices were placed as a single layer on 1 m^2 trays and dried in a passive solar dryer located on a farm in this territory (coordinates 6°45'13.6" N, 73°20'20.2" W). Drying temperatures ranged from 30°C to 50°C, with the relative humidity inside the solar dryer varying between 15% and 60%. The weight of each tray was monitored every 60 minutes using an electronic scale (D&M Tools, China) until the weight of the plantain slices remained constant. The drying process lasted 8 hours, resulting in a final moisture content of 8.5%.

A blade mill (Tecnal, Brazil) was used to process the dried plantain into flour, using a 20-mesh sieve to obtain a grain size of 0.8 mm. The flour was packaged in plastic hermetic bags and stored at room temperature (23 °C ± 2°C).

2.3. Cookie formulation and preparation

For the experimental design, cookies prepared using only wheat flour served as the control, and three levels of plantain flour substitution (25%, 50% and 100%) were assessed while maintaining the other ingredients constant. The cookie formulations are shown in Table 1. Both formulation and preparation of cookies were adapted based on reported by Bawa et al. [11,24].

Table 1. Formulation of cookies with incorporation of unripe plantain flour

	% (weight of each ingredient/weight of cookie dough)			
Ingredient	**T100P0**	**T50P50**	**T25P75**	**T0P100**
Wheat flour	30.25	15.12	7.56	0.00
Plantain flour	0.00	15.12	22.69	30.25
Oatmeal flour	13.80	13.80	13.80	13.80
Cassava starch	2.35	2.35	2.35	2.35
Margarine	22.03	22.03	22.03	22.03
Refined sugar	4.41	4.41	4.41	4.41
Unrefined whole cane sugar	7.34	7.34	7.34	7.34
Egg	7.34	7.34	7.34	7.34
Whole milk	4.41	4.41	4.41	4.41
Honey	5.87	5.87	5.87	5.87
Vanilla essence	1.47	1.47	1.47	1.47
Cinnamon powder	0.29	0.29	0.29	0.29
Baking soda	0.44	0.44	0.44	0.44

T100P0: 100% wheat flour, 0% unripe plantain flour; **T50P50**: 50% wheat flour, 50% unripe plantain flour; **T25P75**: 25% wheat flour, 75% unripe plantain flour; **T0P100**: 0% wheat flour, 100% unripe plantain flour

Margarine was thawed to room temperature (23 °C ± 2°C) and cut into pieces. It was placed in a mixing bowl and textured for 5 minutes at low speed using a KitchenAid stand mixer (model KSM195PSMI, USA). Unrefined whole cane sugar and refined sugar were added gradually and mixed at medium speed for at least 5 minutes until fully incorporated. The eggs were beaten to combine the whites and yolks, then added gradually to the mixture to avoid breaking the cream formed in the previous step. Vanilla essence and honey were added afterward and blended for 3 minutes. In a separate bowl, wheat flour, unripe plantain flour, oatmeal flour, cassava starch, cinnamon powder, and baking soda were mixed with a spatula. The dry mixture was gradually incorporated into the wet mixture. Mixing time during this step was kept brief to ensure all ingredients were combined while minimizing gluten development.

The cookie dough was stored in airtight plastic bags and refrigerated at 5 °C ± 2°C for at least 20 minutes. The chilled dough was portioned into pieces weighing 5 g ± 0.5 g, and each piece was shaped into a ball. The balls were formed into portions with a diameter of 20 mm ± 2 mm and a height of 10 mm ± 2mm.

The cookies were placed individually on a silicone mat, leaving a 15 mm space between each cookie. A Hamilton Beach countertop oven (model 31104D, USA) was preheated to 160 °C for 15 minutes. The cookies were baked for 16 minutes and then cooled to room temperature on the silicone mat. After cooling, the cookies were stored in hermetically sealed plastic bags.

2.4. Color

The color parameters of the cookies (L*, a*, and b*) were measured for six different samples of the same formulation using a Hunter Lab colorimeter (model Colorquest-X, USA). In these calculations, L* represents the lightness ranging from 0 (black) to 100 (white), a* represents the red–green coordinate, and b* the yellow–blue coordinate. The subscript 0 (L_0*, a_0*, b_0*) denotes the corresponding color parameters of the control cookies prepared with 100% wheat flour. The total color difference (ΔE) between the control cookies and those with plantain flour inclusion was calculated using equation 1 [25].

$$\Delta E = \sqrt{\left[\left(L_0^* - L^*\right)^2 + \left(a_0^* - a^*\right)^2 + \left(b_0^* - b^*\right)^2\right]} \quad (1)$$

Chroma (C*), which indicates the intensity of the color in the cookies, was calculated using Equation 2 [25].

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

The hue angle (h*) was calculated using Equation 3

$$h^* = \tan^{-1}\frac{b^*}{a^*} \quad (3)$$

2.5. Physical characteristics

The weight (g) of each cookie was measured using an analytical scale (Mettler Toledo, Switzerland). Thickness (mm) and diameter (mm) were measured using a digital Vernier caliper (Simhevn, China) [23, 36].

2.6. Hardness Measurement

The hardness of the cookies was measured using a Stable Micro Systems texture analyzer (model TA.TX plus, England), following an in-house methodology established at the Bromatology Lab from the Faculty of Agrarian Sciences of the National University of Colombia. The instrument was configured as follows: test mode: compression, pre-test speed: 1 mm/sec, test speed: 3 mm/sec, post-test speed: 10 mm/sec, distance: 10 mm, trigger force: 50 g, and break mode: off. Measurements were performed on seven cookies from each formulation.

2.7. Proximate Composition

The moisture content of the samples was determined by drying in an oven at 105°C for 12 hours (AOAC, method 950.46) [26]. Nitrogen content was determined via Kjeldahl acid digestion, and the result was multiplied by 6.25 to calculate the protein content (AOAC, method 920.152) [26]. Fat content was determined using Soxhlet extraction (AOAC, method 963.15) [26], and ash content was estimated by combusting the samples in a muffle furnace at 550°C (AOAC, method 940.26) [26]. Total carbohydrate content was calculated by difference as shown in Equation 4.

Carbohydrate content (%) = 100 – Moisture (%) – Protein (%) – Total fat (%) – Ash (%) (4)

2.8. Sensory Analysis

A consumer sensory analysis was conducted with 100 anonymous participants, consisting of adult men and women aged 18-50 years, following the guidelines suggested in the Colombian technical standard GTC 293 [27]. Four cookie formulations were presented without revealing their identity to consumers, using a three digits non-consecutive code. A questionnaire was designed to collect feedback, and the test was divided into two steps. First, consumers rated each cookie on a 5-point hedonic scale, where 1 indicated “I extremely dislike it” and 5 indicated “I extremely like it”. Attributes evaluated included color, texture, aroma, flavor and overall perception. Consumers were also asked whether they would buy the cookie (yes or no).

In the second part of the test, consumers ranked the cookies, assigning #1 to the most liked and #4 to the least liked. Consumers were allowed to provide additional feedback and suggestions on the cookies they tasted.

2.9. Statistical Analysis

All instrumental measurements were performed in six replicates for each formulation. Mean values were calculated for each physicochemical and sensory attribute. A one-way analysis of variance (ANOVA) at a 95% confidence level was applied to evaluate the effect of cookie formulation (plantain flour substitution level) as the independent factor on the measured response variables, including physical, color, proximate composition, and sensory attributes. When significant differences were detected, Tukey's Honestly Significant Difference (HSD) post hoc test was used to identify differences between formulations. In addition, Principal Component Analysis (PCA) was performed in MATLAB® to explore relationships between sensory attributes and physicochemical characteristics as the level of plantain flour increased in the formulations.

Finally, a Total Ranking Test was conducted using DART® software (Talete, Italy) to identify the best cookie formulation. This analysis applied a utility and desirability analysis, a widely recognized multi-criteria decision-making method, based on defining a partial value function that transforms the value of each criterion into a comparable scale [28]. To analyze the parameters for each sample, the average or median values of each variable were calculated, and an autoscaling process was applied to normalize the data for comparison across variables. The utility and desirability functions for each cookie formulation were defined using Equations 4 and 5 [28].

$$U_i = \sum_{j=1}^{p} w_j \cdot t_{ij} \quad 0 \le U_i \le 1 \tag{4}$$

$$D_i = t_{i1}^{\,w1} \cdot t_{i2}^{\,w2} \cdot \ldots t_{ip}^{\,wp} \quad 0 \le D_i \le 1 \tag{5}$$

Where represents each alternative evaluated, is the value obtained after the linear transformation of the initial value for each alternative; and corresponds to each criterion evaluated, with a total of criteria. is the weight assigned to each criterion, ranging between 0 and 1, with the sum of the weights of all criteria equaling 1. The result of the analysis is a value between 0 and 1, where the optimal treatment is expected to have a value of 1 for both criteria, as described by Pavan and Worth [28].

To evaluate the cookie formulations, the parameters listed in Table 2 were used to apply the Total Ranking Test.

Table 2. Parameters for applying the Total Ranking Test to cookie formulations

Criterion	Transformation function	Optimal condition	Weighting
Color (sensory analysis)	Sigmoid	Maximum	0.10
Aroma (sensory analysis)	Sigmoid	Maximum	0.10
Texture (sensory analysis)	Sigmoid	Maximum	0.10
Flavor (sensory analysis)	Sigmoid	Maximum	0.10
Global perception (sensory analysis)	Sigmoid	Maximum	0.20
L*	Sigmoid	Maximum	0.02
a*	Sigmoid	Maximum	0.01
b*	Sigmoid	Maximum	0.02
Hardness (N)	Triangular	Intermediate	0.05
Moisture content (%)	Inverse sigmoid	Minimum	0.02
Ash content (%)	Sigmoid	Maximum	0.02
Fat content (%)	Inverse sigmoid	Minimum	0.05
Protein content (%)	Sigmoid	Maximum	0.05
Fiber content (%)	Sigmoid	Maximum	0.11
Carbohydrate content (%)	Inverse sigmoid	Minimum	0.05

The sigmoidal function was selected to evaluate most of the variables because it effectively captures how small changes in the variable initially have little effect. Once certain thresholds are reached, improvements in the variable lead to faster changes, which then stabilize.

3. RESULTS

3.1 Physicochemical Analysis

A proximate composition analysis was performed on the solar-dried plantain flour. The results are presented in Table 3, alongside the composition of plantain flour reported by other authors [29,30] and the proximate composition of wheat flour for comparison [23,31,32]. Moreover, the results of the proximate composition analysis (on a wet basis) for the cookies are shown in Table 4.

Table 3. Proximate composition of plantain and wheat flours.

	Solar dried plantain flour	Plantain flour	Wheat flour
Moisture (%)	8.48 ± 0.01	6.15-8.63	8.58-12.67
Ash (%)	2.13 ± 0.02	2.01-3.69	0.87-1.30
Fat (%)	0.41 ± 0.05	0.49-2.63	0.94-1.60
Protein (%)	2.33 ± 0.17	2.47-5.59	10.56-12.75
Fiber (%)	7.23	0.81-4.27	0.36-0.61
Reference:		[29,30]	[23,31,32]

Table 4. Proximate composition of cookies.

	T100P0	T50P50	T25P75	T0P100
Moisture (%)	8.23±0.01ab	7.36±0.03a	7.97±0.76ab	8.49±0.01b
Ash (%)	1.22±0.01a	1.48±0.01b	1.67±0.02c	1.81±0.02d
Fat (%)	19.23±0.21b	19.09±0.25ab	18.83±0.08a	18.85±0.14ab
Protein (%)	8.94±0.12d	6.93±0.16c	5.77±0.04b	4.71±0.09a
Fiber* (%)	3.38	3.98	4.11	4.76
Carb (%)	59.00	61.42	61.65	61.38

* Fiber was determined from a single measurement; therefore, values are reported descriptively without standard deviation and were not included in the statistical analysis.

Values are expressed as mean ± SD. Letters in the same row indicate significant differences ($p < 0.05$).

3.2. Physical Attributes and Hardness of Cookies

Figure 1 illustrates the appearance of the cookies after baking, and Table 5 provides the dimensions, weight, and hardness for each formulation. No noticeable differences were observed during the kneading process across the four formulations. To ensure a fair comparison of the final appearance, all formulations were baked under the same conditions and for the same duration.

Figure 1. Visual appearance of baked cookies

Table 5. Physical attributes and hardness of cookies.

Formulation	Diameter (mm)	Thickness(mm)	Weight (g)	Hardness (N)
T100P0	26.33±0.34ab	13.94±0.23a	4.10±0.06a	29.94±3.91c
T50P50	26.15±0.43a	14.53±0.37b	4.14±0.05ab	19.76±5.53b
T25P75	26.49±0.38ab	14.40±0.53ab	4.21±0.04b	22.71±3.25b
T0P100	26.82±0.48b	14.58±0.44ab	4.17±0.05ab	14.81±1.23a

Values are expressed as mean ± SD. Different letters in the same column indicate significant differences ($p < 0.05$).

3.3. Color

The color analysis results for the cookies are presented in Table 6. The last three columns include the chroma value (C*), which represents the color intensity or saturation, and the hue angle (h), which defines the shade.

Table 6. Color parameters of cookies.

	T100P0	T50P50	T25P75	T0P100
L*	59.09±4.09a	60.77±3.70a	62.59±3.85a	57.85±6.06a
a*	9.08±0.75a	9.68±1.13a	8.87±1.32a	9.28±1.12a
b*	28.09±0.85ab	30.01±1.03b	29.90±0.86ab	27.46±2.24a
C	29.53±0.93a	31.55±1.17a	31.21±1.04a	29.00±2.31a
h	72.10±1.27a	72.15±1.78a	73.51±2.16a	71.31±1.95a
ΔE	0	2.62	3.95	1.40

Values are expressed as mean ± SD. Letters in the same row indicate significant differences ($p < 0.05$).

3.4. Sensory Analysis

While physical and chemical properties provide objective data on the cookie formulations, consumer preferences and sensory perceptions are equally important for assessing product acceptability. The sensory analysis evaluated how participants perceived different formulations based on taste, texture, aroma, and overall satisfaction. The results are summarized in Table 7.

Table 7. Sensory test results for cookies.

Formulation	Color	Aroma	Texture	Flavor	Global perception
T100P0	3.87 ± 0.97b	3.98 ± 0.93c	4.05 ± 0.93b	3.94 ± 0.94b	3.96 ± 0.80b
T50P50	3.44 ± 0.96a	3.83 ± 0.93bc	3.86 ± 0.85ab	3.64 ± 1.04ab	3.71 ± 0.81ab
T25P75	3.26 ± 0.83a	3.75 ± 0.91ab	3.59 ± 0.97a	3.57 ± 0.99ab	3.52 ± 0.78a
T0P100	3.22 ± 0.95a	3.44 ± 1.11a	3.57 ± 1.14a	3.41 ± 1.05a	3.46 ± 0.85a

Values are expressed as mean ± SD. Letters in the same column indicate significant differences ($p < 0.05$).

3.5. Statistical Analysis

3.5.1. Principal Component Analysis

Principal Component Analysis (PCA) was conducted to provide a comprehensive understanding of how physicochemical and sensory attributes contributed to the differences among the formulations. Figure 2 summarizes the results, highlighting the clustering of the formulations and the variables driving their differentiation. The first two principal components (PC1 and PC2) explained a cumulative variance of approximately 89%, with PC1 accounting for 66.38% and PC2 contributing 22.28%. This high cumulative variance demonstrated that the two components effectively captured the variability in the dataset.

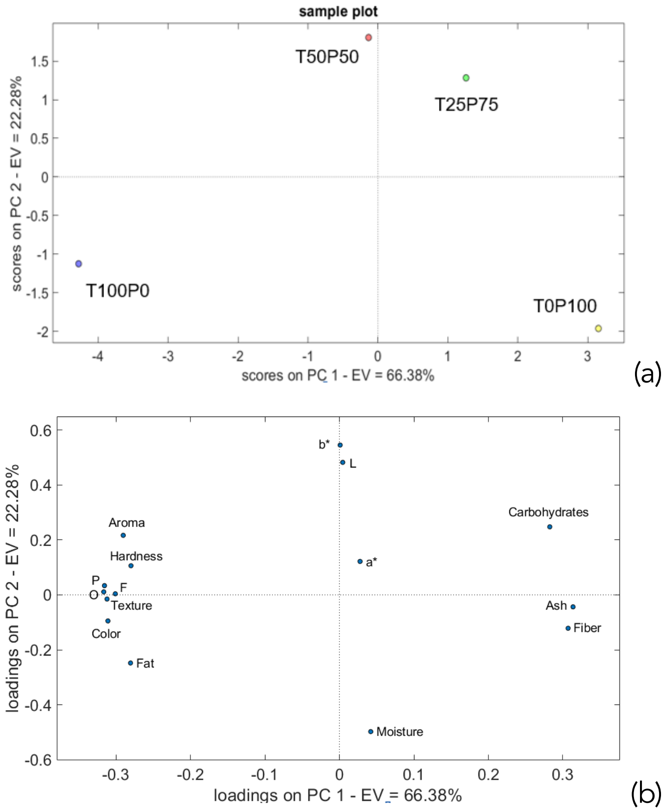

Figure 2. Principal Component Analysis results for the physicochemical characterization of cookies. (a) Score Plot, (b) Loading Plot. P: protein; O: overall; F: flavor

3.5.2. Total Order Ranking Test

The PCA analysis was complemented by a Total Order Ranking Test, with results shown in Table 8, presenting the utility and desirability scores ranging from 0 to 1, along with the ranking positions of the different cookie formulations. These scores provide a holistic evaluation of the formulations, integrating both sensory and nutritional attributes into the overall assessment.

Table 8. Results of Total Order Ranking Test for cookies.

Ranking	Formulation	Desirability	Utility
1	T50P50	0.581	0.644
2	T100P0	0	0.452
3	T25P75	0	0.371
4	T0P100	0	0.253

The sigmoidal function used for evaluation was particularly suitable for sensory variables, such as color, flavor, and texture, where consumer perception tends to plateau at a certain threshold. For example, enhancing the flavor of a cookie beyond a certain point may not result in any further perceptible improvement. This approach penalizes low values or those far from the ideal while rewarding high or optimal values, but without infinite gains. For sensory variables such as color or flavor, significant improvements were observed, but beyond a certain point, further increases no longer lead to proportional changes in consumer acceptance.

Sensory variables, including color, aroma, texture, flavor, and overall acceptance, were maximized because consumer perception plays a key role in product acceptance. Among these, the "overall" sensory rating received the highest weight (0.20) as it integrates individual sensory perceptions into a final, more significant assessment. Color parameters such as L, a*, and b* were also maximized, as they are important in consumer perception. These parameters indicate higher saturation or brightness, qualities typically preferred by consumers. However, the b* parameter was given slightly less influence due to its comparatively lower impact on the final consumer decision. Darker or more intensely colored cookies are often perceived as more appealing and indicative of desirable Maillard browning [33]. Besides, higher L* values help avoid excessive darkening caused by high levels of plantain flour or over-browning during baking [34].

For texture, an intermediate value was targeted using a triangular transformation, as both overly hard and overly soft cookies tend to be less desirable. Texture was assigned a moderate weight (0.05), reflecting its importance without overshadowing sensory acceptance attributes. Moisture content was minimized to promote increased shelf life and a crispier texture, though its weight was kept low (0.02), as immediate sensory qualities were prioritized.

Nutritional attributes were also considered. Ash content, indicative of mineral composition, was maximized to ensure a desirable mineral profile, though it was assigned a low weight (0.02) due to its limited direct influence on consumer acceptance. Fat content was minimized to enhance the nutritional profile of the cookies, with moderate consideration for its essential role in texture and flavor. Protein content was maximized for its contribution to nutritional value and assigned a moderate weight (0.05).

Fiber content, which plays a significant role in the nutritional value and health benefits of the product, was given a relatively high weight (0.11). Carbohydrate content was minimized to align with dietary health considerations, though its weight remained moderate, recognizing the necessity of carbohydrates in baked products.

4. DISCUSSION

4.1. Physical Attributes and Hardness of Cookies

The variable that showed the most significant difference among the formulations was hardness, which was higher in cookies without plantain flour. This finding is consistent with other studies where wheat flour was partially or fully replaced with plantain flour [11]. The reduction in hardness observed with the inclusion of plantain flour can be attributed to its high water absorption capacity [35]. When plantain flour replaced wheat flour, it diluted the gluten networks formed by glutenin and gliadin present in the dough. Although cookie dough does not develop a fully structured gluten network due to its low hydration and limited mixing, a partial gluten structure is still formed when wheat flour is present. As the proportion of plantain flour increased, this partial gluten network weakened, leading to a reduction in the hardness of the final product [11,23]. The correlation coefficient between cookie hardness and the proportion of plantain flour in the formulations was -0.7, indicating an inverse relationship: as the amount of plantain flour increased, hardness decreased. This difference could be partially explained by the similarity in the formulations, resulting in minimal variation in ingredient interactions and, consequently, in the structural properties of the cookies.

The average weight of all cookie formulations was 4.16 g ± 0.06 g, representing a 16% reduction from the initial dough weight. This information is valuable for formulation processes and material balance considerations in large-scale production. In terms of dimensions, the diameter and thickness of the cookies increased by 32% and 43%, respectively, relative to the initial dough dimensions. The greatest increase in dimensions was observed when wheat flour was completely substituted with plantain flour (100%). This outcome is likely due to the high-water retention capacity of plantain flour, which is attributed to its fiber and starch content [35]. However, other studies have reported different outcomes, such as flatter and thinner cookies when wheat flour was replaced with plantain flour [11]. The differences between our results and those reported in other studies may be explained by variations in formulation and processing conditions, which strongly influence cookies physical characteristics. Cookie expansion is affected by factors such as dough hydration, sugar and fat content, type of plantain flour used, fiber level, and baking temperature [36]. In our study, the higher water retention capacity of the plantain flour likely increased dough viscosity and internal steam generation during baking, promoting upward expansion and greater thickness. In contrast, other studies may have used flours with different starch or fiber profiles, higher sugar or fat levels, or baking conditions that favored horizontal expansion and produced flatter cookies. Such compositional and process differences can therefore lead to opposite trends when wheat flour is replaced with plantain flour.

4.2. Physicochemical Analysis

Solar-dried plantain flour stands out due to its distinct composition compared to plantains from other geographic regions and wheat flours, reflecting the influence of processing methods, raw material characteristics, and environmental conditions. The reported fiber content (Table 3) is particularly significant, offering potential benefits for addressing dietary fiber deficiencies. Additionally, the ash content indicates the presence of valuable minerals, supporting its use in nutrient-rich formulations.

To further understand the impact of plantain flour substitution on the nutritional profile of the cookies, a comprehensive physicochemical analysis was conducted (Table 4). This analysis provided insights into the moisture, ash, fat, protein content, as well as the color attributes of the various formulations. The moisture content did not show a consistent trend with the addition of plantain flour. Although plantain flour has a higher water retention capacity, this property mainly influences dough rheology rather than the final moisture of the baked cookies. The increased binding of water during mixing produces a more viscous, less spreadable dough, which contributes to greater thickness and volume during baking [37]. However, final moisture content is determined by moisture migration and evaporation during baking, which do not necessarily follow the same trend as water absorption capacity of the raw flour. Therefore, a greater volume can coexist with a moisture content that does not show a consistent trend among formulations.

On the other hand, the mineral content, reflected in the ash content, significantly increased as plantain flour was incorporated. This increase is consistent with the higher mineral content of plantain flour, which is rich in essential minerals such as calcium (9.4-11.4 mg/100 g), potassium (328-528 mg/100 g), and magnesium (24-29 mg/100 g) [11,29]. Fat content showed small but statistically significant differences among formulations. The cookies with 100% wheat flour had the highest fat content (19.23%), which was significantly greater than the 25% wheat–75% plantain formulation (18.83%). The other two formulations (50:50 and 0:100) showed intermediate values and were not statistically different from either group. The slight decrease in fat at higher plantain flour levels may be related to the lower intrinsic fat content of plantain flour compared with wheat flour, as reported in Table 3. In addition, the greater water-binding capacity could modify fat migration and retention during baking, resulting in marginally lower extractable fat values [38]. However, because the main fat source in cookies is the added shortening, the influence of flour substitution on total fat content is limited, which explains the modest variations observed. The protein content of the cookies decreased as the proportion of plantain flour increased. The T100P0 formulation (100% wheat flour) had a protein content of 8.94%. With the addition of plantain flour, the protein content decreased to 6.93% in T50P50, 5.77% in T25P75, and 4.71% in T0P100. This reduction is attributed to the lower protein content of plantain flour (approximately 3%) [29,35] compared to the 10% protein content of wheat flour [6,23]. The maximum observed reduction in protein content was 47.2%.

Conversely, fiber content increased with higher levels of plantain flour substitution. While the T100P0 formulation contained 3.38% fiber, this increased to 3.98% in T50P50, 4.11% in T25P75, and 4.76% in T0P100. This increase is attributed to the higher fiber content of plantain flour compared to wheat flour, making the cookies with plantain flour an excellent source of dietary fiber. The observed fiber increase, reaching up to 41%, is associated with potential health benefits, such as improved digestive health and enhanced satiety [22,29,39].

Reported proximate composition for plantain flour varies widely in the literature. For example, Umoh et al (2024), in a study drying green plantain under different methods, found ash contents between 3.94% and 4.33%, crude fiber between 2.89% and 3.11%, and carbohydrate (by difference) around 85–88% [40]. Adeogun et al. (2021) reported, for unripe plantain flour, moisture of 13.1%, crude fiber 2.45%, ash 3.10%, fat 1.6 % and carbohydrate 70.3 % [41]. Earlier work on blanched plantain flours reported crude fiber between 1.8 and 2.9%, as well as ash around 2.0–2.2 % [30]. In some banana/plantain-based flours the total dietary fiber has been reported up to 15.5% depending on variety and processing [42]. These differences confirm that proximate composition of plantain flour strongly depends on cultivar, maturity, processing and drying method.

In summary, across the formulations, a clear compositional shift was observed as wheat flour was progressively replaced with plantain flour. The 100% wheat formulation (T100P0) showed the highest protein (8.94%) and fat (19.23%) contents, along with the lowest ash (1.22%) and fiber (3.38%). As plantain flour incorporation increased (T50P50 and T25P75), protein content declined (to 6.93% and 5.77%), while ash and fiber rose, reflecting the higher mineral and fiber levels of plantain flour. Fat content showed only small absolute differences across treatments, with a slight but statistically significant reduction at 75% substitution (18.83%). The 100% plantain cookie (T0P100) presented the lowest protein (4.71%) and the highest ash (1.81%) and fiber (4.76%), confirming the compositional influence of plantain flour. For moisture, T0P100 exhibited the highest value (8.49%). Overall, the results demonstrate a progressive nutritional transition from a wheat-based to a plantain-based product as substitution levels increased.

Replacing wheat flour with plantain flour has been reported to reduce protein content while increasing crude fiber and mineral content, an effect documented in biscuits prepared with plantain–chickpea blends, where fiber rose significantly compared with 100% wheat biscuits [43]. Also, cookies made with esterified or raw plantain flour show lower digestible starch and lower estimated glycemic index compared with wheat-flour cookies, suggesting potential benefits for glycemic control [6]. Moreover, composite-flour cookies that include plantain flour achieve enhanced ash (mineral) and fiber levels, illustrating how plantain flour incorporation can boost nutritional value and diversify food formulations [44].

4.3. Color

Table 6 reveals that there were no significant differences in brightness (L*) or the a* coordinate, which represents the green-to-red color spectrum. However, significant differences were observed in the b* coordinate, which reflects the blue-to-yellow color spectrum. The color change (ΔE) values for cookies incorporating plantain flour are also displayed. Notably, cookies with formulations T50P50 and T0P100 exhibited noticeable differences exceeding 2 units, which are perceptible to the human eye [11]. The most pronounced color variation was observed in the formulation containing 25% wheat flour and 75% plantain flour (T25P75).

Previous studies on replacing wheat flour with plantain or other alternative flours have reported significantly different L*, a*, and b* values, as well as higher ΔE levels, compared to those observed in this study [6,11]. These differences are largely attributed to the distinct color properties of the ingredients used and the changes induced during baking. In this study, the incorporation of plantain flour lightened the dough color. The reduced presence of wheat flour decreased the extent of the Maillard reaction during baking, as the lower levels of glutenin and gliadin, proteins that typically interact with sugars, resulted in reduced caramelization [45,46].

4.4. Sensory Analysis

The sensory evaluation of the four cookie formulations provided valuable consumer feedback, highlighting both strengths and areas for improvement. Statistical analysis showed significant differences in color ratings, with T100P0 receiving the highest score (3.87 ± 0.97), being higher than the other formulations. Cookies with higher proportions of plantain flour (T50P50, T25P75, and T0P100) received lower color ratings, with T0P100 scoring the lowest (3.22 ± 0.95). Free-form comments echoed these results, with consumers noting that some cookies appeared pale or visually unappealing. As previously mentioned, this could be due to a reduced Maillard reaction in formulations with lower wheat content. Plantain flour contains a higher proportion of resistant starch and non-reducing sugars [47], which do not readily participate in the Maillard reaction compared to the reducing sugars found in wheat flour. To address this, adjusting baking time or temperature could enhance browning and improve the color of plantain-containing cookies [48].

In terms of aroma, T100P0 received the highest score (3.98 ± 0.93), while T0P100 scored the lowest (3.44 ± 1.11). Free-form feedback suggested that the aroma of plantain-based cookies, particularly T0P100, was perceived as weak or lacking distinctiveness. Some participants described the aroma of T100P0 and T50P50 as “artificial” or ”intense,” which could indicate an imbalance in flavorings or other additives. Experimentation with natural flavor enhancers or the inclusion of spices may help enrich the aroma and balance the intensity, thereby improving consumer satisfaction.

Texture ratings declined as the proportion of plantain flour increased. T100P0 received the highest score

(4.05 ± 0.93), while T0P100 scored the lowest (3.57 ± 1.14). Most consumers described the texture of T25P75 and T50P50 as dry, soft, or grainy. These descriptions likely reflect the absence of gluten in plantain flour, which affects dough cohesiveness and smoothness. To mitigate these issues, adjustments to dough hydration (e.g., adding more water or other source of moisture) or modifications to the baking process could improve texture. Additionally, optimizing the ratio of plantain to wheat flour may help achieve a better balance between structural integrity and texture.

Flavor ratings showed a clear trend, with T100P0 (3.94 ± 0.94) and T50P50 (3.64 ± 1.04) receiving higher ratings compared to T25P75 (3.57 ± 0.99) and T0P100 (3.41 ± 1.05). Free-form feedback highlighted that T0P100 was sometimes perceived as overly sweet or "unfriendly," while T100P0 and T50P50 were described as having "artificial" or "intense" flavors. This suggests that the higher levels of plantain flour contribute to a sweetness some consumers find excessive, while the flavor profile of wheat flour-based formulations may require adjustments to reduce synthetic notes. Incorporating natural flavor enhancers, and balancing sweetness with neutral flavor components could help create a more balanced and pleasing flavor profile.

The global perception scores showed that T100P0 (3.96 ± 0.80) and T50P50 (3.71 ± 0.81) received statistically similar ratings, suggesting that a 50% substitution of plantain flour did not significantly reduce overall acceptability. Despite differences in specific sensory attributes, these two formulations were considered highly acceptable by consumers. Free-form feedback suggested that consumers generally found the cookies tasty, with favorable texture and aroma, despite subtle differences among formulations. The comparable global perception scores for T100P0 and T50P50 indicates that a 50% plantain flour substitution level provide a satisfactory balance, maintaining overall acceptability while incorporating a local and alternative ingredient.

The sensory evaluation results demonstrated that plantain flour can be successfully incorporated into cookie formulations, offering an alternative to wheat flour without substantially compromising consumer acceptance. While higher levels of plantain flour (as in T25P75 and T0P100) led to decreases in specific sensory attributes such as texture and flavor, the overall acceptance of these formulations remained positive. T100P0 was the most favored in terms of color, aroma, and texture, while T50P50 achieved a balance that maintained positive sensory attributes. Future adjustments to formulation, baking parameters, and ingredient ratios can further optimize the sensory profile of plantain-based cookies, offering potential for broader consumer acceptance and market success.

4.5. Statistical Analysis

4.5.1. Principal Component Analysis

The score plot (Figure 2a) shows the distribution of cookie formulations along the two principal components. The T100P0 formulation is positioned at the negative extreme of PC1, indicating its distinct characteristics compared to the other formulations. In contrast, the T0P100 formulation was located at the positive extreme of PC1, underscoring the substantial differences in physicochemical and sensory attributes between these two formulations. The intermediate formulations, T25P75 and T50P50, were situated along the positive axis of PC2 and are closer to each other. This intermediate positioning reflects a more balanced combination of attributes derived from both wheat and plantain flours, demonstrating a moderate integration of sensory and nutritional qualities in these formulations.

The loadings plot (Figure 2b) provides deeper insights into the specific variables that influenced the differentiation of the cookie formulations. Quadrant III, associated with the T100P0 formulation, is characterized by high protein content and favorable sensory attributes, such as global acceptance, texture, flavor, and aroma. These results align with the sensory evaluation, where T100P0 received the highest ratings in these categories. However, this formulation had a lower fiber content, limiting its overall nutritional value. Quadrant IV, corresponding to the T0P100 formulation, highlights attributes such as high fiber and ash content (indicative for mineral composition), and reduced moisture content. These characteristics reflect the nutritional advantages of plantain flour, which is known to be rich in dietary fiber, minerals, resistant starch, and polyphenols [39,49].

The intermediate formulations, T25P75 and T50P50, were positioned in Quadrants I and II, where attributes related to color (L*, a*, b*) dominated. These formulations exhibited brighter and more vibrant colors, a desirable trait for consumer appeal. The balanced positioning of these formulations in the PCA plot indicated that they successfully integrate sensory acceptability with improved nutritional profiles. A clear trend emerged as the proportion flour increased: higher fiber and mineral content was observed, but sensory scores for attributes such as flavor, texture, and overall acceptance declined. These results underscore the nutritional benefits of plantain flour, while indicating potential sensory challenges as its proportion increases.

Overall, the incorporation of plantain flour alters the structural properties of the dough by reducing the proportion of gluten-forming proteins (gliadin and glutenin) derived from wheat flour. Although cookie dough does not develop a fully elastic gluten network due to its low hydration, the partial protein network formed in wheat-based formulations still contributes to structural integrity [50]. As plantain flour replaces wheat flour, this protein–starch matrix becomes progressively weaker, reducing the dough's ability to retain structure during baking and affecting the texture of the final product [47]. This structural weakening also contributes to the observed reduction in cookie hardness.

Additionally, the starch behavior in plantain flour differs from that of wheat starch, as plantain flour contains a higher proportion of resistant starch and non-gluten proteins. These starch fractions absorb more water but do not contribute to the same viscoelastic properties as wheat starch, resulting in a softer and more crumbly cookie texture. The increased water retention can also influence baking dynamics, affecting the final moisture content and mouthfeel [47].

One of the most noticeable effects of plantain flour substitution is the reduction in browning, attributed to a diminished Maillard reaction. Since gluten proteins provide a significant portion of free amino groups, their reduction in plantain-based formulations limits the extent of this reaction. Furthermore, plantain flour has a different sugar composition, with a higher content of resistant starch and fewer reducing sugars, further restricting browning [51]. Consequently, cookies with higher plantain flour content appear paler and less golden-brown compared to their wheat-based counterparts. To mitigate this effect, future formulations could explore the inclusion of protein-rich ingredients (e.g., egg whites, milk proteins) or controlled sugar modifications to enhance Maillard reaction activity and improve visual appeal.

The PCA results underscore the potential of T25P75 and T50P50 formulations as optimal compromises between sensory and nutritional attributes. These formulations represented promising candidates for product development, offering a balance between consumer acceptability and the nutritional advantages of plantain flour. The inclusion of plantain flour enhanced the fiber and mineral content while reducing carbohydrate levels, addressing consumer demands for healthier alternatives [10,39].

4.5.2. Total Order Ranking Test

The T50P50 formulation was the most favorable, receiving the highest scores for desirability (0.581) and utility (0.644). This formulation, with a balanced mix of wheat and plantain flours, offered an optimal compromise between sensory qualities and nutritional enrichment, consistent with its position in the PCA plot.

In contrast, the T100P0 formulation, despite its favorable sensory characteristics, ranked second (desirability = 0, utility = 0.452). The absence of plantain flour resulted in lower nutritional content, particularly in fiber and minerals. Since the sensory test was conducted anonymously, participants likely favored T100P0 based purely on its sensory qualities, without bias towards its nutritional profile.

Formulations with higher plantain flour content, such as T25P75 and T0P100, ranked lower in both desirability and utility. The T25P75 formulation (desirability = 0, utility = 0.371) and T0P100 (desirability = 0, utility = 0.253) offered significant nutritional benefits, including higher fiber and mineral content, but faced challenges in sensory acceptance, due to the flavor and texture changes induced by the plantain flour.

The results underscore the importance of sensory characterization in determining consumer preferences, even as nutritional enrichment gains prominence. The T50P50 formulation received the highest overall acceptability, likely due to a well-balanced interaction between plantain and wheat flour, which optimized both texture and flavor perception. The presence of 50% wheat flour retained sufficient gluten to maintain dough structure, ensuring an appealing texture that was neither too crumbly nor too hard. Additionally, the combination of wheat and plantain starches contributed to a favorable moisture balance, preventing excessive dryness or gumminess.

In terms of flavor, the moderate substitution level allowed the natural sweetness of plantain flour to enhance overall taste without overpowering familiar cookie flavors. This balance likely contributed to higher hedonic ratings in sensory analysis. The

Maillard reaction was still sufficiently active at this substitution level to produce desirable browning and caramelized flavor notes, which were more pronounced compared to formulations with higher plantain flour content. These factors together support why T50P50 emerged as the most preferred formulation.

4. CONCLUSIONS

The novelty of this work lies in the application of solar drying for producing plantain flour, a simple, low-cost method that remains underexplored in bakery formulations, and in the use of advanced ranking and multivariate tools to integrate physicochemical, structural, and sensory attributes for formulation optimization. Incorporating plantain flour significantly increased the fiber content of the cookies and modified their composition, resulting in formulations with enhanced nutritional characteristics compared with the control. Among the substitution levels tested, the 50% plantain flour formulation provided the most favorable balance of sensory properties, including texture, flavor, and overall acceptability, demonstrating its suitability for developing consumer-oriented baked products.

In addition to its functional and sensory performance, the use of plantain flour offers a valuable strategy for utilizing surplus or underused plantain crops, thereby reducing post-harvest losses and supporting the development of locally sourced ingredients. Solar drying enabled the production of a stable flour with appropriate functional properties for cookie manufacturing, contributing to the creation of long-lasting, shelf-stable products suitable for regions with limited processing infrastructure. Therefore, the incorporation of plantain flour into cookie formulations presents a practical and scalable approach for developing products with improved fiber content and acceptable sensory quality.

Future research should focus on expanding the applications of plantain flour in diverse food products, exploring its long-term health impacts, and optimizing its production for large-scale commercial use, as well as on strategies to improve protein content by incorporating complementary sources (e.g., legumes, dairy proteins, or insect-based flours). Additionally, studies on consumer preferences and sensory optimization will be critical for tailoring these products to specific market needs.

ACKNOWLEDGEMENTS

The authors would like to thank the Association of Farmers and Beekeepers from Serranía de los Yariguíes – APISY, located in Galan, Santander, Colombia.

FUNDING

This work was supported by the Universidad Nacional de Colombia [grant number: Hermes 55304]. Ms. Fajardo-Ariza received partial funding for the completion of her Master thesis from the Faculty of Agricultural Sciences, Universidad Nacional de Colombia [grant number: Hermes 59992].

CONFLICTS OF INTEREST

The authors declare no conflict of interest associated with this article.

DECLARATION OF GENERATIVE AI IN SCIENTIFIC WRITING

During the preparation of this work, the authors used OpenAI© in order to improve the readability and language of the work. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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