

Agri-food model update and evaluation of pesticide residues, physicochemical, and microbiological quality in *bocadillo* production from the Santander-Boyacá region, Colombia

Actualización del modelo agroalimentario y evaluación de residuos de pesticidas, fisicoquímica y calidad microbiológica en la producción de bocadillo en la región de Santander-Boyacá, Colombia

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University of Antioquia
Medellin, Colombia

Affiliations

^a Colombian Agricultural Research Corporation - AGROSAVIA, Tibaitatá Research Center, Cimpa headquarters, km 2 of the old road to Cite, Barbosa, Santander, Colombia.

^b Universidad de Tolima, campus principal, Av. 42 #1B-1, Ibagué, Tolima, Colombia.

^c Colombian Agricultural Research Corporation - AGROSAVIA, Central Headquarters, km 14 on the road from Mosquera to Bogotá, Mosquera, Cundinamarca, Colombia.

^d Colombian Agricultural Research Corporation - AGROSAVIA, La Libertad Research Center, km 17 on the road from Villavicencio to Puerto López, Villavicencio, Meta, Colombia.

*Corresponding

Oscar Mendieta
omendieta@agrosavia.co

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Oscar Mendieta ^{a*}, Carlos Andrés Rodríguez ^b, Luis Gabriel Bautista ^c, Leidy Yibeth Deantonio-Flrido ^a, Mónica Idalí Plazas ^a, Ivonne Ximena Cerón ^b, Yury Paola García ^d

ABSTRACT

BACKGROUND: Guava (*Psidium guajava* L.) is a nutritionally rich fruit widely consumed fresh or processed. In the Santander-Boyacá region of Colombia, guava is used to produce *bocadillo*, a traditional confection made by concentrating guava pulp with sugar, with annual production reaching approximately 24,300 tons. Despite its economic and cultural relevance, there is a lack of up-to-date information on this agri-food model, particularly regarding the current characterization of raw materials and the microbiological safety of the final product. Furthermore, there is no available information regarding pesticide residues that may persist in *bocadillo* due to the use of agrochemicals in guava production. **OBJECTIVE:** This study aimed to update the agri-food model for *bocadillo* production in the Santander-Boyacá region, Colombia, and evaluate the safety and quality of the product from physicochemical, microbiological, and pesticide residue perspectives. **METHODS:** Fifteen *bocadillo* factories in the municipalities of Barbosa, Guavatá, Moniquirá, and Vélez were analyzed. Raw materials (guava), intermediate products (pulp and jelly), and the final product (*bocadillo*) were characterized using 15 physicochemical parameters. Microbiological analyses and pesticide residue screenings were conducted on *bocadillo* samples. Data were analyzed for variability and compliance with national/international standards. **RESULTS:** Most physicochemical parameters showed no significant differences between factories, indicating high standardization in raw materials and final product. The updated agri-food model allowed the identification of critical factors along the supply chain, from primary guava production to marketing of the final product (*bocadillo*). Microbiological quality met safety thresholds in all samples, but 53.3% contained pesticide residues, with some exceeding regulatory limits. **CONCLUSIONS:** The study demonstrated that *bocadillo* factories in the Santander-Boyacá region follow standardized production practices. The updated agri-food model identified production processes, operating methods (*modus operandi*), and interactions between supply chain actors. The final product was microbiologically suitable; however, the presence of pesticide residues in some samples highlights the need for stricter agricultural controls. These findings lay the groundwork for improving food safety and sustainability in the traditional guava-processing agroindustry.

Keywords: Guava, *bocadillo*, agri-food model, food safety.

RESUMEN

ANTECEDENTES: La guayaba (*Psidium guajava* L.) es una fruta de gran valor nutricional, ampliamente consumida fresca o procesada. En Colombia, en la región de Santander-Boyacá, la guayaba se utiliza para producir bocadillo, un dulce tradicional elaborado mediante la concentración de pulpa de guayaba con azúcar, con una producción anual de aproximadamente 24.300 toneladas. A pesar de su relevancia económica y cultural, existe una falta de información actualizada sobre este modelo agroalimentario, en particular sobre la caracterización de las materias primas y la seguridad microbiológica del producto final. Asimismo, se desconoce la posible presencia de residuos de plaguicidas en el bocadillo por la aplicación de agroquímicos en los cultivos. **OBJETIVO:** Actualizar el modelo agroalimentario de producción de bocadillo en la región de Santander-Boyacá, Colombia, y evaluar la seguridad y calidad del producto desde las perspectivas fisicoquímica, microbiológica y de residuos de plaguicidas. **MÉTODOS:** Se analizaron quince fábricas de bocadillo en los municipios de Barbosa, Guavatá, Moniquirá y Vélez. Se caracterizaron las materias primas (guayaba), los productos intermedios (pulpa y jalea) y el producto final (bocadillo) mediante 15 parámetros fisicoquímicos. Se realizaron análisis microbiológicos y análisis de residuos de plaguicidas en muestras de bocadillo. Se analizó la variabilidad y el cumplimiento de las normas nacionales e internacionales de los datos. **RESULTADOS:** La mayoría de los parámetros fisicoquímicos no mostraron diferencias significativas entre las fábricas, lo que indica una alta estandarización de las materias primas y el producto final. El modelo agroalimentario actualizado permitió identificar factores críticos a lo largo de la cadena de suministro, desde la producción primaria hasta la comercialización del producto final. La calidad microbiológica cumplió con los umbrales de seguridad en todas las muestras, pero el 53,3 % contenía residuos de plaguicidas, y algunos superaron los límites reglamentarios. **CONCLUSIONES:** El estudio demostró que las fábricas de bocadillos en la región de Santander-Boyacá siguen prácticas de producción estandarizadas. El modelo agroalimentario actualizado identificó los procesos de producción, los métodos operativos (*modus operandi*) y las interacciones entre los actores de la cadena de suministro. El producto final fue microbiológicamente adecuado; sin embargo, la presencia de residuos de plaguicidas en algunas muestras resalta la necesidad de controles agrícolas más estrictos. Estos hallazgos sientan las bases para mejorar la seguridad alimentaria y la sostenibilidad en la agroindustria tradicional de procesamiento de la guayaba.

Palabras clave: Guayaba, bocadillo, modelo agroalimentario, seguridad alimentaria.

1. INTRODUCTION

Guava (*Psidium guajava* L., Myrtaceae) is a perennial tree cultivated in tropical and subtropical regions worldwide (1). It is rich in nutrients, such as amino acids and sugars, as well as bioactive compounds (2), including phenolic acids, flavonoids, and ascorbic acid (3–5). Guava can be eaten fresh or used in the production of processed products due to its highly perishable nature and consequently short shelf life. To ensure the profitable and efficient utilization of guava, it is critical to preserve the fruit and process it into various products. This not only extends its shelf life but also helps stabilize prices during periods of overproduction (6).

India is the world's leading producer of guava, with an annual production of approximately 2.5 million tons. The country accounts for 45% of global guava production, followed by Indonesia, China, and Mexico (7). Various guava-based products are produced worldwide. For example, Mexico produces "ate," a sweet made from guava or other fruits such as pear, sapote, or mango (8). Additionally, "dulce de membrillo," which originated in Europe, particularly in countries like Spain, has spread to various Latin American countries (9). In Brazil, "gioabada" is a paste made from ripe guavas, water, and sugar (10).

In Colombia, the area planted with guava in 2022 was 12,292 hectares, resulting in a production of

163,115 tons. The departments with the highest fruit production were Santander, Meta, and Boyacá, accounting for 39%, 19%, and 7% of the national production, respectively (11). The predominant guava cultivars in Colombia include the ecotypes and varieties: "Regional Blanca," "Regional Roja," "Ráquira Blanca," "Guavatá Victoria," "Palmira ICA 1" (pear guava), "ICA Roja 2," and the more recent "Corpoica Carmín 0328" and "Corpoica Rosa-C." The latter two were developed by the Colombian Agricultural Research Corporation (AGROSAVIA) and are noted for their high yields and quality (12). In 2017, it was estimated that approximately 69% of the national guava production was intended for fresh consumption, while the remaining 31% was used to produce derivatives, including *bocadillo* (13).

Bocadillo is a paste obtained by mixing and cooking guava pulp with sugar (14) through a modernized traditional agro-industrial process. In the Santander-Boyacá region of Colombia, the *bocadillo veleño* has a designation of origin (15); it is made with "Regional Roja" (RR) and "Regional Blanca" (RB) ecotypes of guava, grown in the provinces of Vélez and Ricaurte (located in the departments of Santander and Boyacá, respectively), mixed with white sugar and wrapped in bijao leaves (*Calathea lutea*). This product has a dry, rough, and opaque external

appearance; a shiny and moist interior; and an aroma of ripe guava and bijao. The texture is hard and dry on the outside but soft, sandy, and slightly moist on the inside. Its flavor strikes a balance between the acidity of the fruit and the sweetness of the sugar, with a mild acidic undertone dominated by bijao. The color falls within the Pantone ranges 1675-1807 (for RR guava) and 7507-7510 (for RB guava) (15). It is estimated that the provinces of Vélez and Ricaurte produce approximately 24,300 tons of *bocadillo* annually. Of this total, 60% is concentrated in the municipality of Vélez, 22% in Barbosa, and 18% in Moniquirá and Guavatá (16).

The Colombian Technical Standard NTC 5856 (14), Resolution 3929 (17), and Resolution 1407 (18) establish the physicochemical and microbiological requirements that *bocadillo* must meet. However, there is no defined maximum residue limit (MRL) for pesticides in this processed product. While the *Codex Alimentarius* (19) and the European Commission (20) set pesticide MRLs for guava in its raw or fresh state, no specific limits exist for processed guava products such as *bocadillo*. In such cases, the European Union's default level of 0.01 mg/kg applies to food products (21).

One of the key challenges in the *bocadillo* agroindustry is ensuring proper agrochemical management by farmers during guava cultivation. Pesticides remain the primary method for controlling pests and diseases in guava crops. However, in many developing countries, the use of pesticides is poorly regulated, which can lead to residues in food products and pose health risks to consumers (22). This issue often arises when farmers harvest fruit without adhering to the required interval between the final pesticide application and harvest (23). In guava-producing regions of Colombia, the crop has been promoted by leading farmers. Management practices, adopted from other production regions or developed empirically (13), have led to excessive or inappropriate use of chemical inputs for pest, disease, and weed control (24). According to the *bocadillo* production process, washing guava may not effectively remove pesticide residues. Peeling the fruit could be a more effective solution (23); however, this is not feasible in the agroindustry, as guava is processed whole.

Based on the available scientific literature, there is no published data in Colombia regarding pesticide residues that may remain in *bocadillo*

due to the agrochemicals applied to crops. Furthermore, updated information on this agri-food model is lacking, particularly concerning the current characterization of the raw material (specifically guavas used in *bocadillo* production) and the microbiological safety of the final product. Therefore, the objective of this study was to conduct an updated diagnostic assessment characterizing the guava agri-food model for *bocadillo* production in the Santander-Boyacá region, Colombia. This included analyzing operational practices, the physicochemical properties of the raw material, intermediate products, and final product, as well as safety assessments of *bocadillo* (focusing on microbiological safety and pesticide residue levels). This research provides a robust foundation for future studies and enhancements to the efficiency and safety of *bocadillo* production.

2. MATERIALS AND METHODS

The diagnosis of the guava agri-food model for *bocadillo* production was conducted in two phases: 1) Baseline assessment, involving the collection and analysis of operational data from *bocadillo* production facilities; 2) Physicochemical characterization of the raw material (guava), intermediate products (pulp and jelly), and the final product (*bocadillo*).

2.1. Geographical location and study population

Data were collected in 2022 across four municipalities in Colombia's Boyacá and Santander departments: Guavatá (5°57'20" N, 73°42'00" W), Vélez (6°00'46" N, 73°40'18" W), Barbosa (5°55'51" N, 73°36'58" W), and Moniquirá (5°52'33" N, 73°34'24" W) (Figure 1). The study area includes 80 *bocadillo* production facilities (15), of which 15 were selected through non-probabilistic convenience sampling. The research employed an observational, cross-sectional, and descriptive design to characterize production conditions and evaluate the food safety aspects of guava *bocadillo* under real operational conditions. Factories were prioritized based on accessibility, willingness to cooperate, and their representation of regional production practices to ensure a diverse and sectorally representative sample. This approach facilitated efficient data collection while capturing the operational variability inherent to *bocadillo* production in the region.

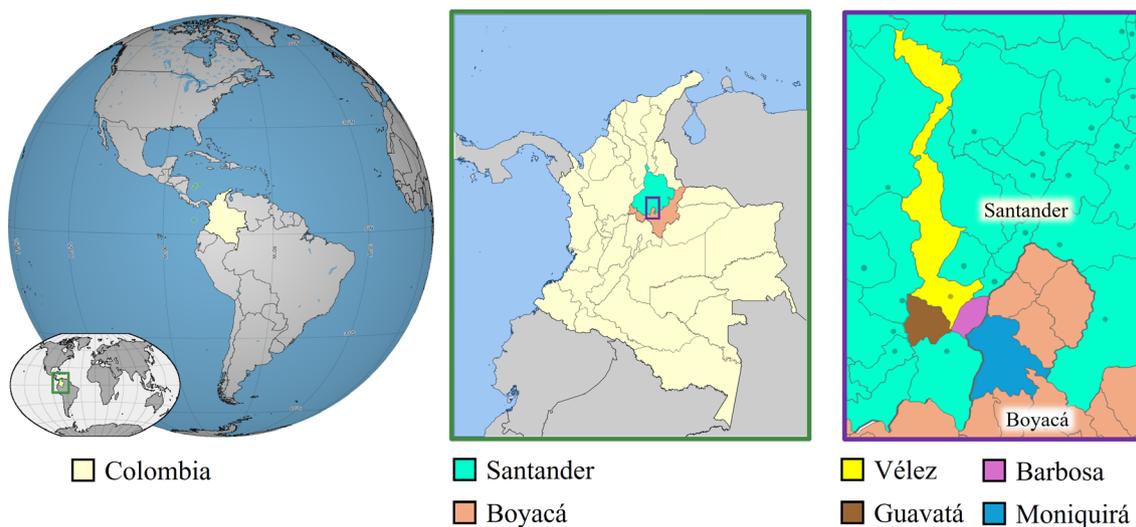


Figure 1. Geographic location of the study area. Source: Authors' elaboration.

2.2. Baseline determination

A semi-structured survey was designed to collect data from *bocadillo* production facilities, focusing on raw materials and inputs, organizational structure, and marketing practices. The survey underwent expert review and a pilot test to assess the clarity and validity of the questions. A descriptive quantitative analysis was conducted to characterize the guava agri-food model for *bocadillo* production. Descriptive statistics (means and frequencies) were calculated for relevant study variables. Using the collected data, an updated agri-food model was developed, mapping key actors and processes. Finally, the model was validated through consultations with industry experts and representatives from surveyed facilities, ensuring its accuracy in capturing the structure and dynamics of the agro-industrial chain.

2.3. Characterization of guava, intermediates, and final product

Samples were collected at each production facility. To account for variability in guava ripeness, three fruits were selected for each maturity stage (semi-ripe, ripe, overripe) of the RR and RB ecotypes. Guavas were randomly chosen from the reception area of each facility and stored at 4 °C to prevent deterioration. Additionally, a maximum interval of 24 hours was maintained between harvest and laboratory analysis to ensure sample integrity.

Pulp and jelly samples were collected from three production batches during the pulping and cooking stages, respectively. These samples were sealed in

airtight glass containers, stored at 4 °C, and analyzed within 24 hours of collection. Additionally, three *bocadillo* samples (1,500 g each) were collected from the same batches prior to packaging using zip-lock bags. All samples were stored in a cool, dry, and clean environment, protected from direct sunlight, until they were analyzed in the laboratory. Each *bocadillo* sample was divided into aliquots: 300 g for physicochemical analysis, 600 g for microbiological analysis, and 600 g for pesticide residue analysis.

2.3.1. Physicochemical analysis

Samples were analyzed at the Analytical Chemistry Laboratory of the Tibaitatá Research Center, part of AGROSAVIA's Cimpa headquarters in Barbosa, Santander Department, Colombia. A total of 15 physicochemical parameters were evaluated (Table 1), including 5 qualitative (shape, size, odor, peel texture, and color) and 10 quantitative (mass, diameter, peel and mesocarp thickness, firmness, moisture content, percentage composition, total soluble solids content, pH, total titratable acidity, and maturity index).

Quantitative parameters were measured in triplicate, with the mean value used for data analysis. Fruit mass was determined using a Mettler Toledo® digital analytical balance (model AB204-S/FACT; Columbus, Ohio, USA). Polar and equatorial diameters and peel-and-mesocarp thickness were measured with a Mitutoyo® digital caliper (model 500-197-30; Aurora, Illinois, USA). Firmness was assessed using a Wagner Instruments® analog penetrometer (model FT30; Greenwich, Connecticut, USA) at three points on

each fruit, both with and without the peel. To quantify the seed, peel, and pulp percentages in guava, the peel was first removed using a manual peeler, and its mass was measured with a digital balance. The peeled fruit was then blended at low speed using an Oster® blender (model BLSTMG-W00; Acuña, Coahuila, México). The mixture was homogenized and passed through a #18 sieve (1.0 mm mesh) to separate the seeds, which were air-dried at room

temperature for 6 hours. Seed mass was measured using a digital analytical balance. Pulp mass was calculated via mass difference by subtracting the peel and seed masses from the total fruit mass. Percentages were calculated by dividing the value of each component by the total mass of the fruit, multiplied by 100.

Table 1. Physicochemical parameters analyzed in the samples: guava, pulp, jelly, and *bocadillo* (BO).

Parameter	Sample				Analytical method	Reference
	Guava	Pulp	Jelly	BO		
Shape (pyriform, ovoid, spherical)	x				Geometric description	-
Size (large, medium, small)	x				Diameter perpendicular to the major axis of the fruit	(25)
Odor (strong and penetrating, soft and pleasant)	x				Description of odor intensity	-
Peel texture (smooth, slightly smooth, slightly rough, rough)	x				Tactile description	-
Color ¹	x			x	Colorimetry by sRGB	(26)
Mass (g)	x				Gravimetric method	-
Diameter (mm) ²	x				Direct measurement using a vernier caliper	-
Thickness peel + mesocarp (mm)	x					
Firmness (kg/cm ²) ³	x				Magness-Taylor technique	-
Moisture content (% m/m) ⁴	x			x	AOAC 930.15	(27)
Percent composition (% m/m) ⁵	x				Gravimetric method	-
Total soluble solids content (°Brix)	x	x	x	x	AOAC 932.12	(27)
pH (-)	x	x	x	x	AOAC 981.12	(27)
Total titratable acidity (g citric acid/100 g)	x	x	x	x	AOAC 942.15	(27)
Maturity index	x	x			TSSC/TTA	-

¹ Fruit color was assessed in the peel and pulp. ² Polar and equatorial diameters were measured in the fruit. ³ Fruit firmness was determined both with and without the peel. ⁴ Moisture content was determined in guava (peel, pulp, and whole fruit) and *bocadillo*. ⁵ Fruit composition was expressed as the percentage of peel, seeds, and pulp. TSSC: total soluble solids content, TTA: total titratable acidity.

For moisture content analysis in guava peel and pulp, 5 g of homogenized sample was weighed into a Petri dish using a digital analytical balance. The sample was dried in a Thelco® Precision Scientific oven (model 18; Chicago, Illinois, USA) at 105 °C for 3 hours. After drying, the Petri dish was transferred to a desiccator for 30 minutes to cool, and the final mass was recorded. Moisture content was calculated as $(M1 \times W1 + M2 \times W2) / M3 \times 100$, where *M1*, *M2*, and *M3* are the masses of pulp, peel, and fruit, respectively, and *W1* and *W2* are the moisture contents in pulp and peel, respectively. For the moisture content of the *bocadillo* samples, the same

procedure described above was followed, except the oven temperature was set to 70 °C. This lower temperature was selected to prevent caramelization of sugars and avoid potential alterations to the physicochemical properties of the final product, which has a high sugar content. In contrast, guava pulp and peel were dried at 105 °C, consistent with standard methods for moisture determination in raw fruit matrices where sugar degradation is not a concern.

To measure total soluble solids content (TSSC), pH, and total titratable acidity (TTA) in pulp, jelly,

and *bocadillo*, 5 g of sample was homogenized with distilled water to a final volume of 50 mL using a Velp Scientifica® magnetic stirrer (model F203A0440; Usmate Velate, Italy) for 10 minutes. TSSC was measured with an Anton Paar® digital refractometer (model Abbemat 300; Graz, Austria). pH was determined using a Mettler Toledo® pH meter (model Sevencompact; Columbus, Ohio, USA). TTA was assessed via potentiometric titration with 0.1 N NaOH to an endpoint of $\text{pH } 8.1 \pm 0.2$. TTA was expressed as citric acid content, calculated as $(N \times V \times F) / m \times 100$, where N is the normality of NaOH (0.1 N), V is the volume of NaOH used in the titration (mL), F is the citric acid equivalence factor (0.064), and m is the sample mass (g). The maturity index of guava was calculated as the TSSC/TTA ratio obtained from the pulp.

For qualitative parameters, relative frequency was calculated. Shape, odor, and texture were assessed through visual, olfactory, and tactile sensory evaluations, respectively. Guava size was classified as large (> 50 mm), medium (40–50 mm), or small (30–39 mm) based on the diameter perpendicular to the fruit's main axis (24). Finally, the color of the peel, pulp, and final product was analyzed using sRGB colorimetry. RGB values represent the intensity of red (R), green (G), and blue (B) light emitted by display pixels to reproduce specific colors, encoded on a scale of 0 to 255. The samples were photographed with a 14-megapixel Sony DSC-W330 digital camera equipped with a 1/2.3-inch Super HAD CCD image sensor. Photographs were captured in a white-background chamber under LED-lit conditions to ensure consistent ambient lighting. Digital images were subsequently transferred to a computer, and RGB coordinates from each image were recorded in triplicate using the color analysis tool in Microsoft Paint® software. Average RGB values were tabulated and classified according to the RHS color space (28).

2.4.2. Microbiological analysis

The *bocadillo* samples were analyzed at the CICTA Food Laboratory of the Universidad Industrial de Santander (Piedecuesta, Colombia). The safety of the final product was assessed through the following microbiological analyses: detection of total coliforms (29), detection of fecal coliforms (29), coagulase-positive *Staphylococcus aureus* count (30), *Bacillus cereus* count (31), *Clostridium* sulfite-reducing spore count (32), mold count (33), yeast count (33), detection of *Listeria monocytogenes* (34), and detection of *Salmonella* spp (35).

2.4.3. Pesticide residue analysis

The presence and concentration of pesticide residues in *bocadillo* samples were evaluated. Analyses were conducted at the Pesticide Analysis Laboratory of Primoris (Bogotá, Colombia), a BELAC-accredited facility (ISO/IEC 17025:2017 certified) holding the 057-TEST certification for food safety testing. A multi-method approach was employed to determine pesticide residues, combining gas chromatography-tandem mass spectrometry (GC-MS/MS) and liquid chromatography-tandem mass spectrometry (LC-MS/MS). The procedure included acetonitrile extraction, partitioning, and dispersive solid-phase extraction (dSPE) clean-up, following a modular QuEChERS method compliant with the UNE-EN 15662:2019 standard (36). Samples were screened for 566 pesticides, with 219 quantified via GC-MS/MS and 347 via LC-MS/MS. Additionally, dithiocarbamates, quantified as carbon disulfide equivalents (CS_2), were analyzed, including maneb, mancozeb, metiram, propineb, thiram, and ziram.

2.5. Data analysis

The physicochemical characterization results were analyzed using descriptive statistics, supplemented by ANOVA ($p < 0.05$) and Tukey's honestly significant difference (HSD) test with standard error for mean comparisons.

3. RESULTS AND DISCUSSION

3.1. Baseline: Agro-industry of the *bocadillo*

The *bocadillo* production process, illustrated in Figure 2, begins with guava reception, where workers verify the fruit's suitability for processing. Raw material is either stored in baskets at room temperature for up to 2 days or processed immediately upon receipt. Guavas are then sorted by color (red or white) and categorized by ripeness stage: green, semi-ripe, ripe, or overripe. Semi-ripe and ripe guavas are prioritized for producing high-quality *bocadillo* (37).

Guavas are washed via immersion in potable water to remove impurities (e.g., mud, plant debris, and foreign matter). Fruits in poor condition or with defects, such as damaged tissue, sepals, stalks, or pest-infested areas, are discarded to prevent compromising the final product's quality. The guavas are then rinsed using high-pressure potable water jets. Green guavas may undergo blanching, a thermal process that reduces microbial load, inactivates

enzymes responsible for fruit deterioration, and softens tissues to facilitate subsequent processing stages (37). However, as guava is a climacteric fruit (38), ripening continues during postharvest storage.

This natural progression can be managed in the receiving area, eliminating the need for blanching in some cases.

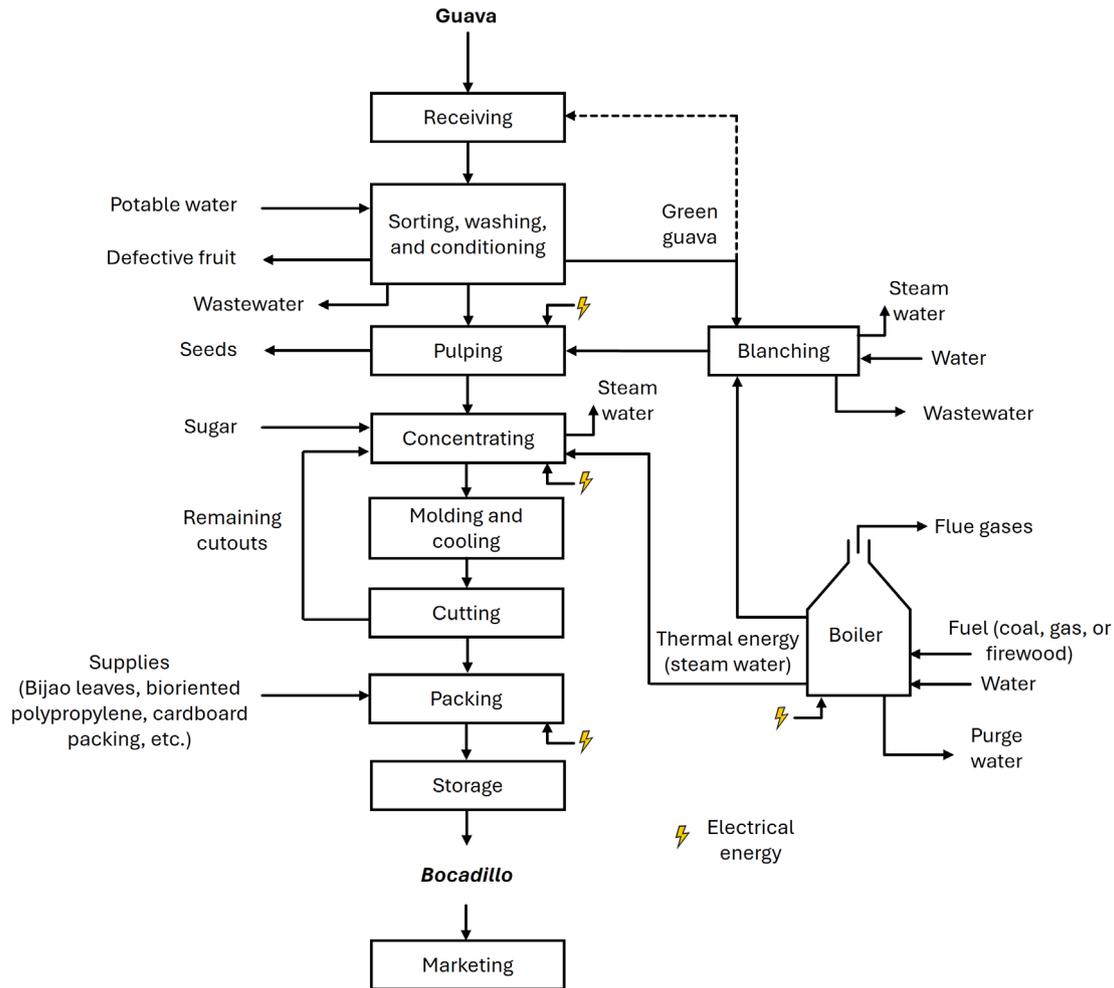


Figure 2. Flowchart of guava *bocadillo* production. Source: Authors' elaboration.

The guava pulp is extracted using a pulper. In this step, the fruit is passed sequentially through a 100-mesh screen and a finer 120-mesh screen to remove seeds and refine the pulp into a smooth consistency. Next, key physicochemical properties of the pulp, including soluble solids concentration, pectin content, and acidity, are measured to inform adjustments to the *bocadillo* formulation. The cooking process occurs in open, round-bottomed kettles equipped with mechanical agitation (65–75 rpm) and steam heating (25–30 psi). As water evaporates from the pulp, sugar is gradually added once the mixture reaches 30 °C. The mixture is concentrated until it reaches the *bocadillo*'s

endpoint, defined as 75–85 °Brix, at which point heating is terminated. The hot jelly is poured into molds and cooled at ambient temperature for 24–30 hours. Once the *bocadillo* achieves a firm consistency, it is cut using manually calibrated cutters adjusted to the desired size for each product format. Production trimmings from this stage are reintroduced into the process for reprocessing. The final product employs a three-tiered packaging system: a) Primary packaging: directly contacts the *bocadillo* (e.g., individual wraps); b) Secondary packaging: groups multiple units (e.g., wooden boxes for bulk handling); c) Tertiary packaging: consolidates secondary packages for distribution.

Traditionally, *bocadillo* is sold as a single-serving snack wrapped in bijao leaves, with wooden boxes serving as secondary packaging for larger quantities. The product is shelf-stable, requiring no refrigeration, and can be stored at 12–24°C. Beyond local markets, *bocadillo* is distributed to supermarkets, institutional buyers, and international export channels (39).

All studied factories are legally registered enterprises. Most facilities (67%) are situated outside the urban cores of their respective municipalities. The workforce ranges from 3 to 18 employees, depending on the factory scale and production volume. Larger facilities exhibit a defined hierarchical structure (40): a) Administration: oversees staff hiring/supervision, raw material procurement, and *bocadillo* sales negotiations; b) Operators: full-time workers responsible for production processes and equipment operation; c) Assistants: temporary laborers hired during peak production periods; and d) Sales personnel: employed by companies with direct retail operations. Notably, some factories operate as family-run units, with all members engaged in traditional *bocadillo* production. *Bocadillo* production facilities in Colombia are regulated by the National Institute for the Surveillance of Medicines and Foods (INVIMA; acronym in Spanish), the national health authority responsible for ensuring compliance with requirements for food production, processing, packaging, storage, transportation, distribution, and commercialization (17). Through ongoing inspections, most surveyed factories demonstrated infrastructure aligned with their operational activities and adherence to good manufacturing practices.

Bocadillo factories primarily source guava from local producers (87% from Santander and 60% from Boyacá). However, due to the crop's seasonal nature and fluctuating market demand, these facilities must also procure guava from other Colombian departments, including Cundinamarca, Huila, Tolima, Norte de Santander, Antioquia, and Caldas. This reliance on external suppliers stems from the fact that only 20% of factories own guava plantations. Coordinating both cultivation and processing is complex, leading most factories to specialize exclusively in *bocadillo* production rather than vertical integration.

The sugar used in *bocadillo* production is primarily sourced from intermediaries who supply it to factories from sugar mills in Colombia's Valle del Cauca department. Bijao leaf packaging for

traditional *bocadillo* originates from local producers in the provinces of Vélez and Ricaurte. The preparation process involves the following steps: a) Harvesting & Sorting: leaves are harvested quarterly and sorted by removing defective specimens; b) Bundling & Treatment: stacked into bundles of 20–25 leaves, rolled to prevent mechanical damage, heat-treated by boiling in water for 30 minutes; c) Post-Treatment: cooled and disinfected with potable water or a sodium hypochlorite solution (40 mL per 10 L of water) (41), sun-dried in open fields to activate photochemical bleaching processes; and d) Final Processing: central veins removed after drying, cut into market-specific sizes, packaged into 500-gram units, transported in baskets to factories, and stored on pallets.

Wooden crates, used as secondary packaging, are typically crafted from balsa wood or other local tree species. Regional manufacturers handle the cutting, drying, and assembling of the wood into crates. Local companies provide additional materials, including cardboard, cellophane paper, and labels. Customized labels are produced by specialized lithographers who tailor designs to meet each factory's specific requirements.

Bocadillo factories diversify their product lines with items like *lonjas*, *tumes*, *rollitos de bocadillo*, and *ojitos de guayaba*, as well as smaller quantities of *manjares*, *veleñitas*, and *bocadillo de frutas* (made with fruits such as blackberry, feijoa, and others). Additionally, some factories supply *bocadillo* to the baking and pastry industries in half-*arroba* blocks (12.5 lb or 5.67 kg), a traditional Colombian unit of measurement. Production capacity varies significantly across factories: 47% of surveyed facilities produce 5–14 tons per week, 13% output 15–25 tons weekly, and 40% operate at under 5 tons per week.

Bocadillo factories market their products locally, nationally, and internationally, with 47% of surveyed facilities employing a hybrid local-national distribution model. Local sales occur through retail outlets near production sites, retail distributors, or mobile vendors at fixed or itinerant points, capitalizing on the product's status as a regional specialty and popular tourist souvenir. Nationally, *bocadillo* is distributed via wholesalers and direct sales to industries that use it as an ingredient. Only 13% of factories export alongside domestic operations. Trade organizations like *ASOVELEÑOS* support commercialization by establishing partnerships with

domestic and international companies interested in purchasing and distributing these products.

Based on the findings, an updated model of the guava agri-food chain for *bocadillo* production was developed (Figure 3), integrating the following key actors: guava producers, primarily regional, though raw materials may seasonally be sourced from producers in other Colombian departments; input suppliers, provide sugar, natural/synthetic packaging, equipment, and machinery, and service providers such as lithography specialists (for printed

materials) and equipment maintenance technicians; processors, factories dedicated to processing guava into *bocadillo*, retail distributors, entities responsible for distributing and selling products through local retail outlets; wholesalers, national and international distributors, often coordinated through producer and distributor associations; consumers, who are end users at the local, national, and global levels. This model offers a conceptual framework for analyzing interdependencies throughout the supply chain, from agricultural production to the commercialization of the final product.

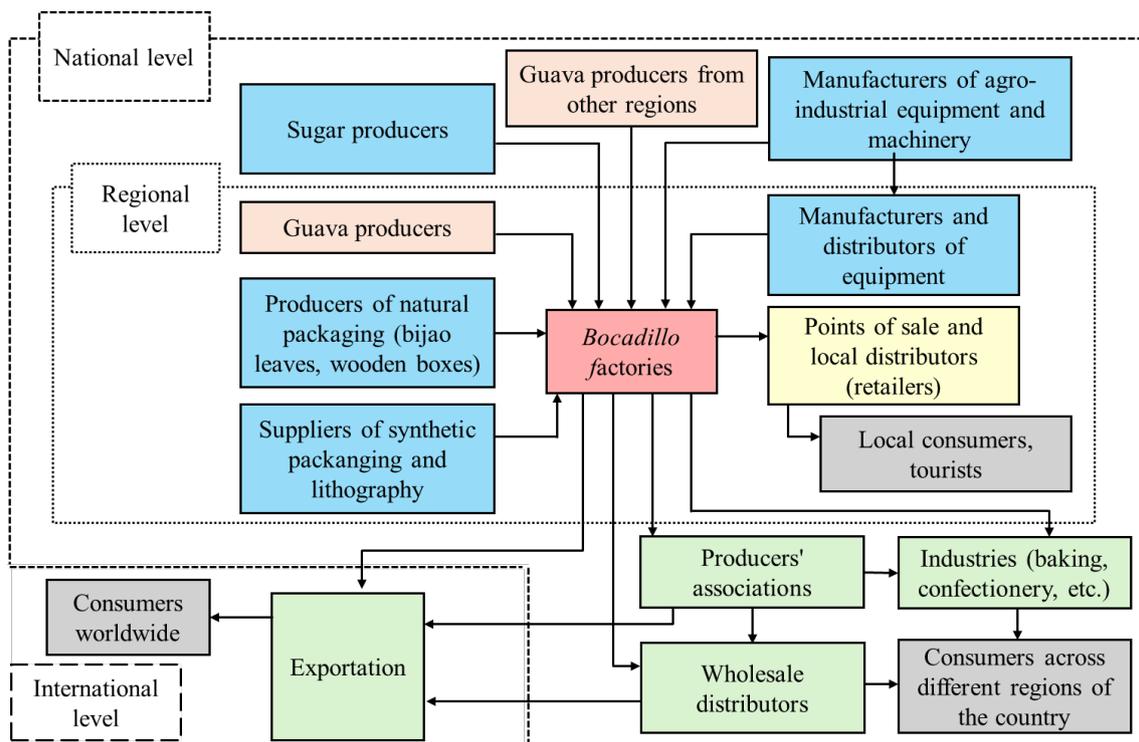


Figure 3. Model of the guava agri-food chain for *bocadillo* production. Source: Authors' elaboration.

3.2. Characterization of guava, intermediates, and final product

3.2.1. Qualitative parameters

Table 2 presents the relative frequencies of qualitative parameters for the two guava ecotypes, RR and RB. The pyriform (pear-like) shape was predominant in the RR ecotype, while the spherical shape dominated in the RB ecotype, with both exhibiting the highest relative frequencies across

the three evaluated maturity stages. These findings align with González et al. (42) and Cantillo et al. (43), who identified these shapes as characteristic of the respective ecotypes. Most guavas from both RR and RB ecotypes were classified as large. Exceptions occurred in the RB ecotype, where medium-sized fruits accounted for 14.29% (ripe) and 21.05% (overripe) of the samples.

Table 2. Relative frequencies (%) of qualitative parameters evaluated in guava ecotypes “Regional Roja” (RR) and “Regional Blanca” (RB) used in *bocadillo* production.

Parameter	Regional Roja (RR)			Regional Blanca (RB)		
	Semi-ripe	Ripe	Overripe	Semi-ripe	Ripe	Overripe
Shape						
Spherical	-	-	5.26	66.67	57.14	63.16
Ovoid	47.62	42.86	36.84	28.57	38.10	31.58
Pyriiform	52.38	57.14	57.89	4.76	4.76	5.26
Size						
Large	95.24	100	94.74	95.24	85.71	78.95
Medium	4.76	-	5.26	4.76	14.29	21.05
Small	-	-	-	-	-	-
Odor						
Strong and penetrating	-	57.14	63.16	4.76	57.14	63.16
Soft and pleasant	100	42.86	36.84	95.24	42.86	36.84
Peel texture						
Smooth	9.52	52.38	47.37	33.33	57.14	57.89
Slightly smooth	66.67	47.62	31.58	52.38	42.86	31.58
Slightly rough	19.05	-	21.05	9.52	-	10.53
Rough	4.76	-	-	4.76	-	-

In both ecotypes (RR and RB), semi-ripe guavas exhibited predominantly soft, pleasant odors, aligning with recommendations for optimal *bocadillo* preparation (37). As ripening progressed to the ripe and overripe stages, odors intensified, becoming strong and penetrating, with the highest relative frequency observed in overripe fruit. Parra and Fischer (44) noted a significant postharvest increase in soluble solids, correlating with heightened flavor and odor intensity.

The texture of the guava peel ranged from smooth to slightly rough. Smooth textures became more prevalent with advancing ripening, whereas rough or mildly rough surfaces occurred in semi-ripe and overripe stages. Quintero et al. (45) attribute these changes to ethylene-induced hydrolytic enzyme

synthesis post-physiological maturity, which drives texture loss, color shifts, sugar accumulation, and acidity reduction.

Figure 4 shows the percentage color distribution in guava peel for the “Regional Blanca” (RB) and “Regional Roja” (RR) ecotypes at three stages of ripeness (semi-ripe, ripe, and overripe). A progressive transition from green tones (light green, medium yellowish-green) to yellow and brown tones (medium yellow, yellowish-brown, light brown) is observed in semi-ripe fruits at more advanced stages of ripeness, reflecting the degradation of chlorophylls and the synthesis of carotenoids during ripening. The RB ecotype exhibits a lighter, more homogeneous color palette, predominantly yellow and light brown at advanced ripeness.

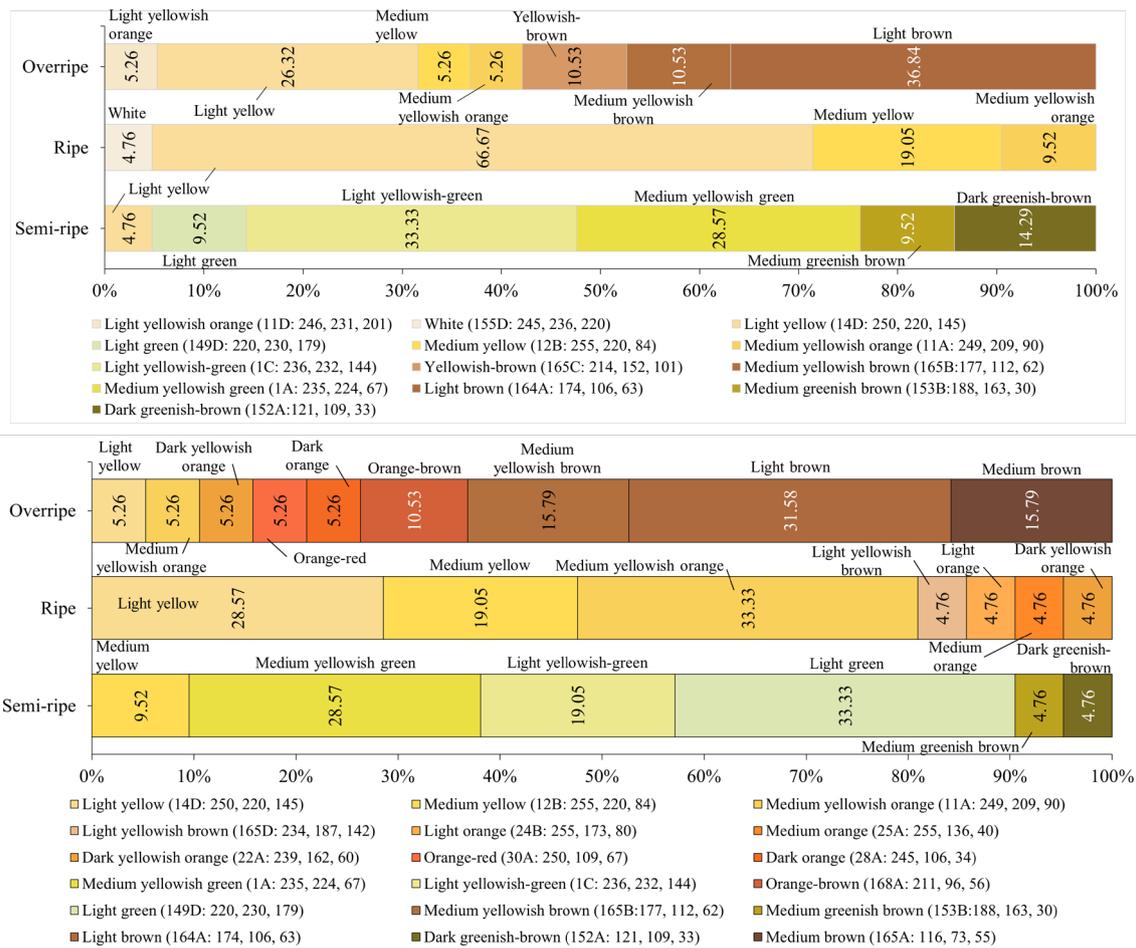


Figure 4. Color distribution (%) in guava peel for ecotypes “Regional Blanca” (RB; top) and “Regional Roja” (RR; bottom). Colors correspond to the RHS classifications (28) and RGB coordinates. Source: Authors’ elaboration.

In contrast, the RR ecotype has greater chromatic variability. Orange and dark brown tones suggest a more intense accumulation of phenolic pigments and carotenoids. In both ecotypes, green tones account for more than 50% in the semi-ripe stage, and yellow and brown tones dominate in the overripe stage, reflecting oxidation and senescence processes in the epidermal tissue. These chromatic variations are technologically relevant, as they enable the establishment of objective criteria for harvesting and classifying the fruit according to its industrial use. A predominantly yellowish shell color indicates optimal ripeness for *bocadillo* production, a crucial factor for achieving consistent quality in the final product.

The green hues in both ecotypes may arise from residual pheophytins and chlorophylls (46), consistent with Castro et al. (47), who observed analogous color shifts (intense green to light green-yellow) in pear guava peels. These chromatic changes align with enzymatic ripening processes:

chlorophyll degradation unmashes pigments like β -carotene (yellow), xanthophylls (orange), and anthocyanins (red/blue) (48).

The color of the guava pulp for the RB and RR ecotypes is depicted in Figures 5a and 5b, respectively. For the RR ecotype, pulp hue and intensity evolved markedly throughout ripening, progressing from light reddish-pink in semi-ripe fruits to medium and dark red tones at full ripeness, and finally to dark purple-red in overripe fruits. This color deepening reflects the accumulation of carotenoid pigments, particularly lycopene and β -carotene, associated with enzymatic activity during ripening and the degradation of chlorophylls. González et al. (46) attributed this chromatic intensification to increased lycopene synthesis, which is responsible for the vivid red coloration typical of this ecotype. In contrast, the RB ecotype displayed a distinct color pattern characterized by lighter tones. Semi-ripe fruits were predominantly white to light yellowish-orange, transitioning to

yellow at ripeness and medium to light brown in overripe stages. This progression indicates oxidative changes and Maillard-type pigment formation rather than carotenoid accumulation. Indeed, González et al. (46) reported no detectable carotenoids in

RB pulp, consistent with its pale yellow coloration. These differences between ecotypes highlight their contrasting biochemical pathways during ripening, which directly influence the visual and sensory attributes of derived products such as *bocadillo*.

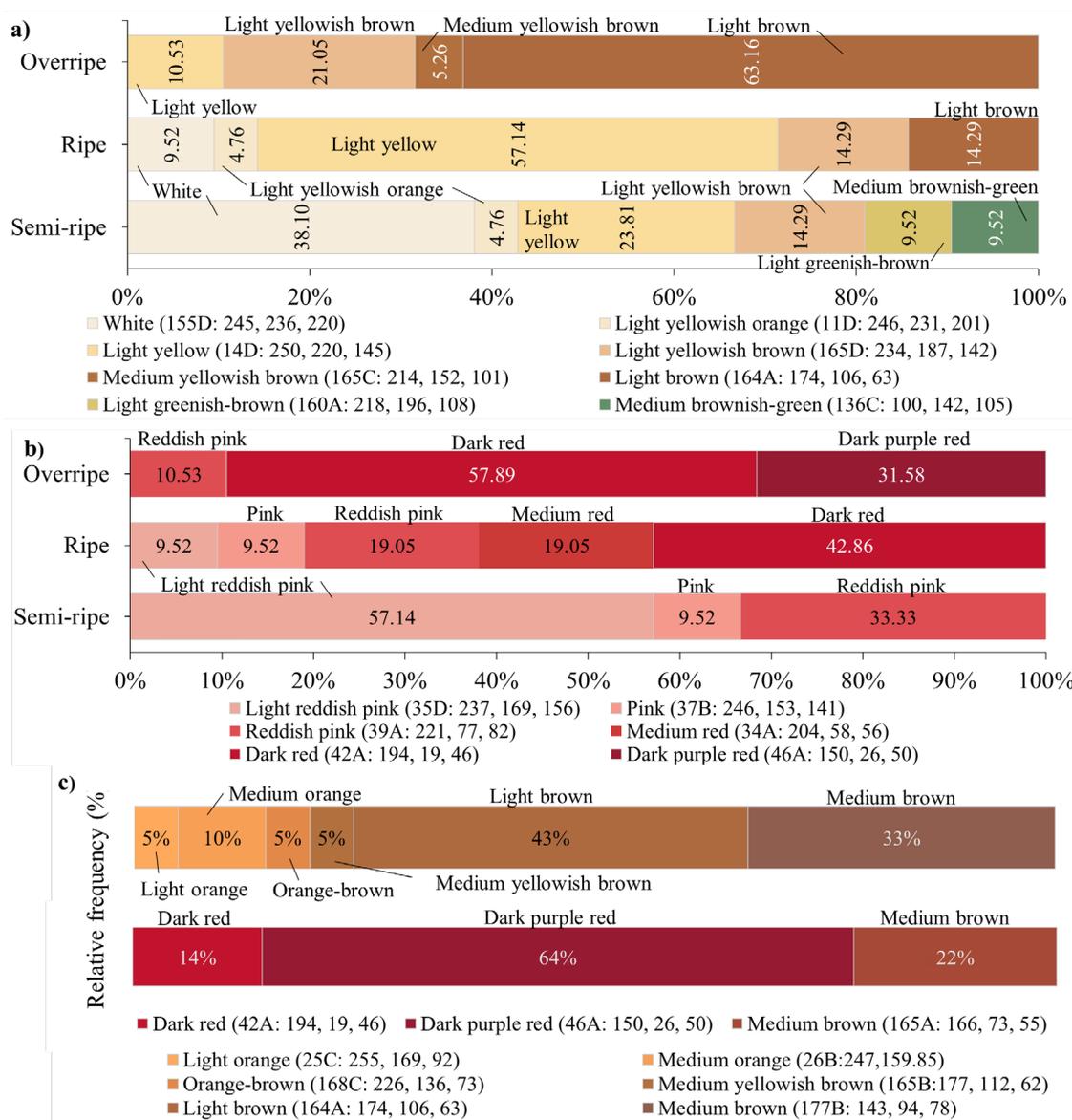


Figure 5. Distribution of pulp color (%) in guava ecotypes “Regional Blanca” (a) and “Regional Roja” (b), and *bocadillo* color obtained from each ecotype (c). Colors correspond to the RHS classifications (28) and RGB coordinates. Source: Authors’ elaboration.

3.2.3. Quantitative parameters

Physical parameters for guava ecotypes RR and RB are summarized in Table 3. Significant differences ($P < 0.05$) were observed between the two ecotypes for mass, polar and equatorial diameters, and

thickness (peel + mesocarp) across all maturity stages, with RR consistently exhibiting higher values than RB. However, these parameters did not vary significantly within either ecotype across maturity stages.

Table 3. Physical parameters analyzed in guava ecotypes “Regional Roja” (RR) and “Regional Blanca” (RB).

Stage of maturity	Parameter	Mean		SD		CV		Min.		Max.	
		RR	RB	RR	RB	RR	RB	RR	RB	RR	RB
Semi-ripe	MASS	125.78	97.57	32.25	17.92	25.64	18.36	73.16	67.09	193.21	134.61
	POLAR_D	69.75	57.41	8.24	3.78	11.81	6.58	54.50	51.36	83.16	63.65
	ECUAT_D	58.42	56.00	5.00	3.56	8.56	6.35	47.16	48.81	68.14	62.43
	PEEL_MESO	8.64	7.58	1.79	1.15	20.72	15.21	5.10	5.78	11.89	10.35
	PEEL_FIRM	4.35	3.37	1.04	0.68	23.82	20.30	2.80	2.17	6.93	4.80
	WPEEL_FIRM	3.37	2.75	1.17	0.67	34.77	24.54	1.43	1.60	6.50	3.93
Ripe	MASS	122.65	94.72	18.13	19.18	14.78	20.25	98.81	64.42	164.72	132.70
	POLAR_D	69.54	57.82	5.64	4.72	8.10	8.16	61.13	50.49	82.72	65.47
	ECUAT_D	59.17	54.91	3.26	4.35	5.51	7.92	53.92	45.43	65.31	63.90
	PEEL_MESO	8.47	7.41	1.25	1.49	14.73	20.14	5.81	4.67	10.56	11.02
	PEEL_FIRM	2.33	2.26	0.50	0.68	21.27	29.87	1.20	1.00	3.40	3.63
	WPEEL_FIRM	1.92	1.70	0.51	0.66	26.70	39.16	0.90	0.60	2.90	3.07
Overripe	MASS	118.95	92.44	24.98	24.61	21.00	26.62	72.21	61.29	189.00	163.61
	POLAR_D	67.80	56.15	9.74	7.89	14.36	14.05	54.73	46.63	86.58	71.36
	ECUAT_D	57.27	54.14	4.72	5.43	8.25	10.03	48.25	46.18	67.05	67.25
	PEEL_MESO	8.20	7.44	1.32	1.92	16.09	25.78	5.68	4.97	11.32	12.29
	PEEL_FIRM	1.05	0.89	0.54	0.26	51.42	29.45	0.53	0.47	2.50	1.50
	WPEEL_FIRM	0.57	0.52	0.40	0.25	69.67	48.86	0.10	0.10	1.40	1.13

SD: Standard deviation, CV: Coefficient of variation, MASS: Mass (g), POLAR_D: Polar diameter (mm), ECUAT_D: Equatorial diameter (mm), PEEL_MESO: Thickness peel + mesocarp (mm), PEEL_FIRM: Fruit firmness with peel (kg/cm²), WPEEL_FIRM: Fruit firmness without peel (kg/cm²).

Firmness, measured both with and without peel, exhibited significant differences ($P < 0.05$) between ripening stages in both guava ecotypes. Fruit at the semi-ripe stage consistently displayed the highest firmness values. This firmness progressively declined throughout ripening until the overripe stage was reached. These findings align with the postharvest firmness ranges reported by Solarte et al. (49) for these ecotypes (RR: 4.42–0.58 kg·cm⁻²; RB: 3.60–0.47 kg·cm⁻²). The underlying mechanism for this characteristic softening is attributed to a substantial increase in cellulase activity within the fruit cell walls during ripening (44). This enzymatic degradation of structural polysaccharides, minimal in green fruit, is a hallmark physiological process driving the textural changes associated with ripening in these climacteric fruits.

Table 4 summarizes the physicochemical parameters evaluated in RR and RB guava ecotypes. No significant differences ($P < 0.05$) were observed in average moisture content (peel, pulp, or total) across maturity stages or between ecotypes. However, significant differences ($P < 0.05$) were observed in peel and pulp content at different maturity

stages. While semi-ripe and ripe guavas showed comparable values, overripe fruit exhibited distinct compositional shifts, with pulp constituting the predominant fraction, followed by peel.

TSSC, pH, and TTA remained consistent across ecotypes, showing no significant variation. Nonetheless, a progressive increase in pH and TSSC was observed from semi-ripe to overripe stages, accompanied by a decrease in acidity. These trends align with findings by Castro et al. (47) and González et al. (46), who reported analogous patterns in climacteric fruits during postharvest ripening. Parra & Fischer (44) and Laguado et al. (50) further corroborate that such shifts typify climacteric fruit behavior. Measured pH values (3.9–4.1) also concur with those documented by Solarte et al. (49) for RR and RB guavas across maturation. The maturity index exhibited the expected behavior, increasing with fruit ripening and showing slightly higher values for the RR ecotype. However, analysis of variance revealed no significant differences ($P < 0.05$) between ecotypes. At the ripe stage, mean maturity indices were 17.78 (RR) and 16.87 (RB), consistent with values reported by Solarte et al. (49).

Table 4. Physicochemical parameters of guava ecotypes “Regional Roja” (RR) and “Regional Blanca” (RB).

Stage of maturity	Parameter	Mean		SD		CV		Min.		Max.	
		RR	RB	RR	RB	RR	RB	RR	RB	RR	RB
Semi-ripe	PEEL_M	84.97	85.67	1.85	1.69	2.18	1.98	82.32	82.75	87.30	88.08
	PULP_M	87.93	87.80	1.83	1.15	2.08	1.31	85.94	86.47	91.25	89.77
	TOTAL_M	83.33	83.84	2.79	1.49	3.34	1.78	78.99	82.03	87.23	85.67
	PEEL_P	10.95	11.28	1.27	2.21	11.63	19.61	9.36	8.73	13.44	15.73
	SEED_P	4.86	4.22	2.66	1.15	54.73	27.35	2.44	2.52	10.12	6.17
	PULP_P	84.19	84.50	2.51	2.57	2.98	3.04	79.40	79.28	87.59	87.07
	BRIX	8.25	8.19	0.68	0.77	8.27	9.37	7.11	6.79	9.13	9.00
	PH	3.93	3.96	0.11	0.13	2.77	3.27	3.71	3.81	4.01	4.16
	TIT_ACID	0.56	0.58	0.07	0.10	12.81	18.06	0.46	0.41	0.64	0.73
	MAT_IND	15.10	14.63	2.50	3.50	16.53	23.96	11.62	10.67	18.31	20.27
Ripe	PEEL_M	85.76	85.63	2.15	1.47	2.50	1.71	81.97	83.93	87.86	87.53
	PULP_M	86.49	87.35	1.70	1.58	1.96	1.81	84.95	84.99	90.03	89.49
	TOTAL_M	83.77	83.02	2.20	2.46	2.63	2.96	80.87	79.57	87.49	86.32
	PEEL_P	9.19	11.66	2.18	2.16	23.67	18.50	4.43	9.41	10.92	15.83
	SEED_P	3.06	4.75	0.95	1.45	30.90	30.55	1.66	2.96	4.68	7.13
	PULP_P	87.75	83.59	2.57	2.79	2.93	3.34	85.55	80.17	92.87	86.83
	BRIX	8.86	8.44	1.06	0.88	11.99	10.39	6.63	7.23	9.98	9.75
	PH	3.95	3.96	0.08	0.14	1.93	3.48	3.84	3.82	4.05	4.18
	TIT_ACID	0.51	0.53	0.09	0.13	18.11	24.02	0.42	0.39	0.66	0.71
	MAT_IND	17.78	16.87	3.75	5.03	21.07	29.84	13.31	11.64	22.29	25.06
Overripe	PEEL_M	85.25	85.20	1.30	1.40	1.53	1.64	82.97	82.45	86.49	86.69
	PULP_M	87.19	87.83	2.45	0.87	2.81	0.99	82.97	86.77	90.41	88.71
	TOTAL_M	83.36	83.76	2.61	2.21	3.14	2.63	80.01	79.61	87.37	86.78
	PEEL_P	14.33	13.37	2.56	1.54	17.88	11.52	12.26	10.41	19.77	15.08
	SEED_P	4.09	4.26	1.14	1.85	27.96	43.52	2.53	1.76	6.07	7.84
	PULP_P	81.59	82.38	2.64	3.01	3.24	3.65	76.99	77.30	85.22	86.30
	BRIX	8.44	8.45	1.03	0.87	12.20	10.27	7.14	7.61	9.96	9.71
	PH	4.02	4.12	0.16	0.21	4.09	5.06	3.82	3.76	4.28	4.39
	TIT_ACID	0.49	0.49	0.12	0.12	25.44	25.04	0.36	0.35	0.67	0.70
	MAT_IND	18.08	18.06	4.42	5.20	24.46	28.82	11.74	13.58	23.47	27.7

SD: Standard deviation, CV: Coefficient of variation, PEEL_M: Peel moisture content (% m/m), PULP_M: Pulp moisture content (% m/m), TOTAL_M: Total moisture content (% m/m), PEEL_P: Percentage of peel (% m/m), SEED_P: Percentage of seed (% m/m), PULP_P: Percentage of pulp (% m/m), BRIX: Total soluble solids content (°Brix), PH: pH (-), TIT_ACID: Total titratable acidity (g citric acid/100 g), MAT_IND: Maturity index (BRIX/TIT_ACID).

Results for pulp, jelly, and final product (*bocadillo*) samples collected during the production process are summarized in Table 5. TSSC increased progressively from pulp to jelly to *bocadillo*, driven by water evaporation and the incorporation of sugar during processing. While no significant differences in TSSC were observed between jelly

and *bocadillo*, both differed markedly from pulp. Average TSSC (75–85°Brix) and moisture content (11–20% m/m) in *bocadillo* samples aligned with NTC 5856 specifications (14). Physicochemical analyses revealed no significant differences in these parameters across the evaluated factories.

Table 5. Physicochemical and microbiological parameters of pulp, jelly, and final product (*bocadillo*) from production factories.

Sample	Parameter	Mean / Result	SD	CV	Min.	Max.
Pulp	BRIX	8.44	0.69	8.17	7.23	10.31
	PH	3.94	0.10	2.63	3.69	4.06
	TIT_ ACID	0.56	0.07	12.80	0.47	0.76
	MAT_ IND	15.19	2.09	13.78	11.02	18.70
Jelly	BRIX	75.39	5.23	6.94	57.18	82.57
	PH	3.96	0.07	1.75	3.78	4.07
	TIT_ ACID	0.51	0.07	14.11	0.39	0.66
<i>Bocadillo</i>	BRIX	77.04	1.23	1.60	74.81	79.59
	PH	3.99	0.08	2.10	3.89	4.16
	TIT_ ACID	0.47	0.06	12.10	0.39	0.56
	BV_ M	0.20	0.02	8.61	0.18	0.23
<i>Bocadillo</i> (Microbiological Analysis)	Detection of total coliforms	< 3	-	-	-	-
	Detection of fecal coliforms	< 3	-	-	-	-
	Coagulase-positive <i>Staphylococcus aureus</i> count	< 100	-	-	-	-
	<i>Bacillus cereus</i> count	< 100	-	-	-	-
	<i>Clostridium</i> sulfite-reducing spore count	< 10	-	-	-	-
	Mold count	< 10	-	-	-	-
	Yeast count	< 50	-	-	-	-
	Detection of <i>Listeria monocytogenes</i>	Absence	-	-	-	-
Detection of <i>Salmonella</i> spp	Absence	-	-	-	-	

SD: Standard deviation, CV: Coefficient of variation, BRIX: Total soluble solids content (°Brix), TIT_ ACID: Total titratable acidity (g citric acid/100 g), PH: pH (-), MAT_ IND: Maturity index (BRIX/TIT_ ACID), BV_ M: Moisture content of the BV (% m/m), detection of total coliforms (MPN/g), detection of fecal coliforms (MPN/g), Coagulase-positive *Staphylococcus aureus* count (CFU/g), *Bacillus cereus* count (CFU/g), *Clostridium* sulfite-reducing spore count (CFU/g), mold count (CFU/g), yeast count (CFU/g), detection of *Listeria monocytogenes* (Absence or presence), detection of *Salmonella* spp (Absence or presence). CFU: Colony-forming units. MPN: Most probable number.

No significant differences were observed in pH across samples, whereas TTA differed significantly between the three stages. As the process progressed, pH increased slightly, accompanied by a decrease in TTA. This phenomenon is likely due to the combined effects of high temperature and elevated sugar concentration, which promote acid degradation or the formation of buffer systems. The maturity index measured in the pulp reflects the random mixture of guavas (varying ripeness stages) used in *bocadillo* production, as practiced by factories. Based on the results, semi-ripe guavas appear to predominate in the process.

The *bocadillo*'s coloration is illustrated in Figure 5c. The product features three distinct layers: a central layer composed of RR ecotype guava, flanked by two outer layers made from RB ecotype guava, with dimensions varying by product type (15). Color analysis revealed dark red and medium brown hues in the RR ecotype layer, dominated by purple-red tones. The RB ecotype layers displayed light orange to medium brown shades.

Standard deviation and coefficient of variation values for physicochemical parameters (pulp, jelly, and *bocadillo*) demonstrated low variability. This suggests consistent use of raw materials with uniform organoleptic and physicochemical properties, as well as highly standardized production processes across regional factories in this study.

3.3. Food safety in the *bocadillo* agro-industry

3.3.1. Microbiological analysis

Microbiological results for *bocadillo* samples are summarized in Table 5. All samples complied with the safety thresholds established by relevant Colombian food safety regulations—NTC 5856 (14), Resolution 3929 (17), and Resolution 1407 (18)—confirming that no microbial counts exceeded thresholds that could pose risks to consumer health. These findings indicate that *bocadillo* is microbiologically safe and that production practices in the studied factories meet safety standards, a conclusion corroborated by Pérez et al. (51), who reported similar compliance for fortified *bocadillo* under NTC 5856 (14).

The absence of pathogenic microorganisms such as *Salmonella* spp. and *Staphylococcus aureus* indicates that the thermal concentration process effectively reduces microbial loads. Additionally, the high soluble solids content (°Brix > 70) creates unfavorable conditions for microbial growth. These factors, together with good manufacturing practices, contribute to the product’s microbial stability during storage. Furthermore, the minimal presence of molds and yeasts indicates that hygiene was maintained appropriately throughout post-processing and packaging. Overall, the microbiological integrity observed in all samples supports the product’s safety for consumption and its potential for commercialization without the need for chemical preservatives.

3.3.2. Pesticide residue analysis

The pesticide residue results for *bocadillo* samples are detailed in Figure 6, which illustrates: maximum detected concentrations of residues (gray bars), percentage of samples containing each residue (values in parentheses), and maximum residue

limits (MRLs) for guava (red square markers) and *bocadillo* (black dotted line). The MRL for *bocadillo* (0.01 mg/kg) follows the European Union’s default threshold (21), which is established for foods lacking compound-specific toxicity data; a relevant approach in Colombia, given the scarcity of studies on pesticide effects in fruits, vegetables, and processed products.

Of the samples analyzed, 46.6% contained no detectable pesticide residues; in contrast, 9 out of the 566 pesticides evaluated were detected in at least one *bocadillo* sample. Within the detected compounds, six insecticides were identified, including pyrethroids (cypermethrin), organophosphates (chlorpyrifos, profenofos), neonicotinoids (thiamethoxam, imidacloprid), and phenylpyrazoles (fipronil). Additionally, three fungicides were detected, classified as triazoles (propiconazole, difenoconazole) and benzimidazoles (carbendazim and benomyl) (51). The pesticides propiconazole, carbendazim and benomyl (grouped), and cypermethrin, were identified in the highest percentage of samples (16.7%, 23.3%, and 33.3%, respectively).

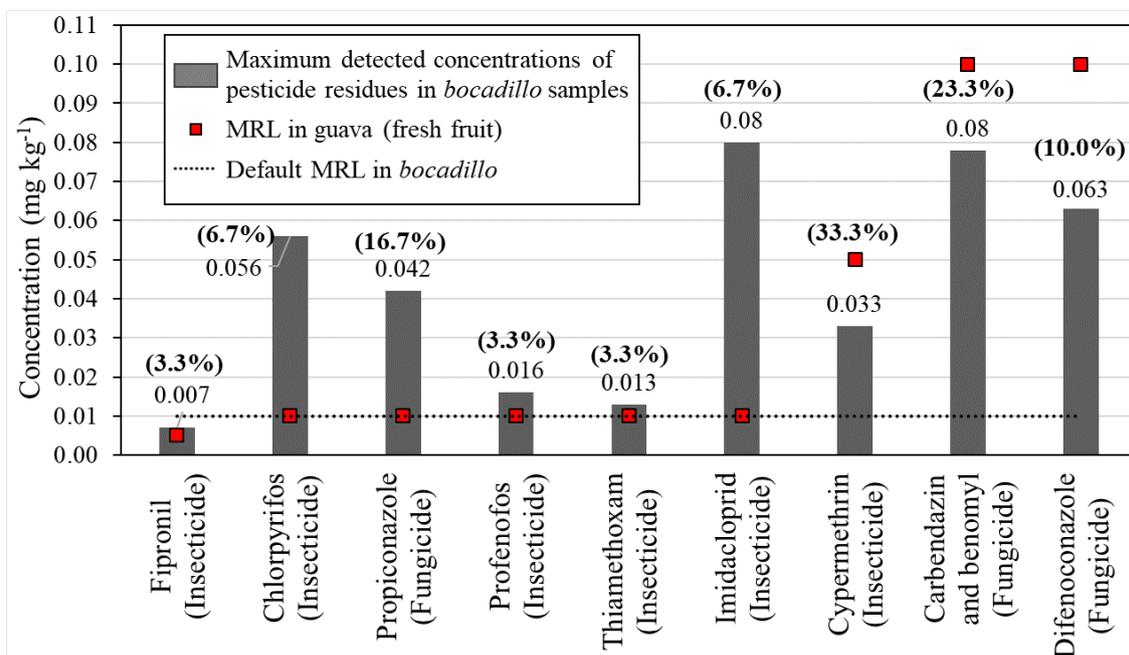


Figure 6. Pesticide residues detected in guava *bocadillo*. Maximum residue limits (MRLs): guava (20); *bocadillo* (default) (21). Source: Authors’ elaboration.

For the pesticides cypermethrin, carbendazim and benomyl (grouped), and difenoconazole, the maximum detected concentrations exceeded the default MRL for *bocadillo*, while staying below the MRL for guava established by the European Commission (20). This indicates that while the detected levels are concerning under stricter criteria, they remain acceptable for unprocessed fruit under European standards. In contrast, chlorpyrifos, propiconazole, profenofos, thiamethoxam, and imidacloprid exceeded both the default MRL for *bocadillo* and the MRL for guava (unprocessed product), posing a higher risk to food safety as their levels surpass limits for both processed and fresh fruit. Fipronil was detected in 3.3% of samples at a concentration exceeding the MRL for guava but not the default MRL for *bocadillo*. While detailed toxicity studies on fipronil in tropical and subtropical fruits justify its lower MRL in fresh produce (20), its detection here suggests a heightened risk of exposure, potentially representing a more significant public health concern.

Although chlorpyrifos and fipronil were detected only in some *bocadillo* samples, the marketing of pesticide products containing these substances is prohibited in Colombia under Resolutions 6365 (53) and 740 (54), as they exceed established risk thresholds for human health and environmental safety. Currently, the registered pesticides for guava crops in Colombia are spinosad, carbaryl, imidacloprid, and lambda-cyhalothrin (55). Among these, only imidacloprid was detected in the analyzed samples.

The results of this study on the analysis of pesticide residues show the use of substances other than those registered in the country for guava cultivation, which could indicate that phytosanitary management in the first link of the agrifood chain and good agricultural practices were not adequate; not only in the study area, but also in other fruit-producing regions of Colombia that supply the *bocadillo* agroindustry. For example, waiting periods (*i.e.*, the time required to wait before harvesting fruit after a pesticide has been applied) have not been observed, pesticide application rates have been exceeded, or multiple pesticides containing the same active ingredient have been combined.

The results of this study on pesticide residue analysis reveal the use of unregistered substances for guava cultivation in Colombia, suggesting inadequate phytosanitary management at the production stage and poor adherence to good agricultural

practices. This issue appears systemic, extending beyond the study area to other fruit-producing regions supplying the *bocadillo* agroindustry. For example, waiting period recommendations (*i.e.*, the time required between pesticide application and harvest) are ignored, pesticide application rates are exceeded, and multiple pesticides containing the same active ingredient are combined. Such noncompliance could compromise the safety of products derived from these practices. Additionally, this study demonstrates that pesticides persist in finished guava *bocadillo* even after processing. In some cases, residue levels remained notably high, suggesting that heat treatment during manufacturing may not completely break down the pesticides; residues might remain intact or only partially break down. To confirm these findings, further research is necessary, particularly studies incorporating comprehensive pesticide analysis with traceability from raw materials to the final product.

4. CONCLUSIONS

This study updated and strengthened the guava agri-food model associated with *bocadillo* production in the Santander-Boyacá region of Colombia. A comprehensive baseline was established through the identification of production processes, operational practices (*modus operandi*), and interactions among actors within the supply chain. The physicochemical characterization of guava, intermediate products (pulp and jelly), and the final *bocadillo* confirmed the standardization of transformation processes and the homogenization of both raw materials and end products across the evaluated factories.

The findings revealed that current *bocadillo*-producing factories comply with Good Manufacturing Practices, ensuring the microbiological safety of the product. Nonetheless, the detection of pesticide residues in *bocadillo* samples, with some levels surpassing the maximum limits established for fresh guava, highlights a potential area of concern. Although these results are preliminary, further investigations are required to assess whether the detected concentrations pose health risks. Strengthening pesticide monitoring systems, enforcing compliance with Good Agricultural Practices, and establishing specific residue limits supported by toxicological studies are key actions to ensure food safety. In addition, reinforcing traceability mechanisms, updating regulatory frameworks, and enhancing the technical capacities of stakeholders throughout the supply

chain will be essential to minimize risks and promote a more sustainable agri-food system.

ETHICAL STATEMENT

Participants in this study provided informed consent by affirming, "I understand that my answers are confidential, and I agree to participate in this study." An affirmative response was required to proceed with the interview, data collection, and sample collection. Researchers explained the study's purpose to participants before they agreed to participate voluntarily. All participants reviewed and acknowledged an informed consent statement before taking part in this study.

CONFLICTS OF INTEREST

The authors of the manuscript declare that there is no conflict of interest related to this work.

AUTHOR'S CONTRIBUTIONS

OAM: Formal analysis, Investigation, Supervision, Visualization, Writing – review & editing. CAR: Formal analysis, Methodology, Writing – original draft, Visualization. LGB: Data curation, Funding acquisition, Project administration, Writing – original draft. LYD-F: Conceptualization, Resources, Validation, Supervision, Writing – original draft. MIP: Investigation, Methodology, Resources, Writing – original draft. IXC: Formal analysis, Supervision, Writing – review & editing. YPG: Formal analysis, Investigation, Methodology, Writing – original draft. All authors reviewed the results, approved the final version of the manuscript, and agreed to its publication.

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