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RESEARCH ARTICLE

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Effect of Fermentation and Drying Practices on the Physical, Chemical and Sensory Characteristics of CCN51 Cocoa Beans (*Theobroma cacao*)

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ABSTRACT

Limited access to technology and the lack of standardized post-harvest practices among cocoa producers contribute to variability in cocoa beans quality, which compromises their commercial value. This study aimed to evaluate the effect of fermentation and drying practices on the physical, chemical composition, and sensory characteristics of CCN51 cocoa beans. Dried fermented beans (DFBs) were obtained from 10 producers in the Monzón Valley (Huánuco, Peru) and analyzed using a completely randomized design (CRD). Both the fermentation (30.2 to 36.5°C and 3 to 6 days) and drying processes (31.9 to 48.0°C and 3 to 6 days) were monitored, revealing variability which was associated with climatic factors and artisanal processing practices. Additionally, the DFBs showed significant differences in weight, thickness and color. Principal component analysis (PCA) and hierarchical cluster analysis (HCA) identified three cluster of producers. Samples from the most representative producer of each cluster were compared with a common variety (control), showing differences in proximate composition, phenolic compounds and FT-IR spectra, revealing specific patterns linked to their origin. In terms of sensory characteristics, the flash profile showed similarities between two producers, while one sample showed similarities with the common variety. These findings highlight the effect of the original post-harvest practices on the compositional characteristics and sensory attributes of cocoa beans.

Keywords: CCN51 cocoa beans; Drying; Fermentation; Flash profile; Polyphenols.

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INTRODUCTION

Cocoa (*Theobroma cacao*) is native to Latin America and is considered as the main raw material for various industries, including cosmetics, pharmaceuticals, and the food sector (Morales-Rodriguez et al., 2024). Among the countries with the highest production worldwide are Côte d'Ivoire, Ghana and Ecuador (Fanning et al., 2023). In recent years, the Peruvian cocoa sector has experienced continuous growth, positioning the country as the eighth-largest exporter globally (Thomas et al. 2023). Despite progress, small-scale producers still continue facing challenges, including limited access to essential information, difficulty in implementing Good Agricultural Practices (GAP) and the necessity for enhanced planting materials and equipment. (Talero-Sarmiento et al., 2025).

Building on previous cultivation experience in Ecuador (Jaimez et al., 2022), the CCN51 genotype was introduced to Peru due to its high yield, disease resistance, and greater tolerance to water stress, features that make it suitable for small-scale irrigated crops. CCN51 is classified as bulk cocoa, characterized by a less complex flavor and aroma profile compared to fine aroma cacao. Therefore, optimizing post-harvest processes through controlled fermentation,

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genetic improvement, and enhancement of sensory profile is necessary to boost competitiveness and strengthen market positioning (Jaimez et al., 2022; Zapata-Alvarez et al., 2024).

Cocoa quality is influenced by multiple factors, including origin, environmental conditions, genotype, fermentation, and processing methods. Cocoa beans are subjected to several post-harvest stages that can affect their chemical composition and, consequently, influence the quality of the final product (Fanning et al., 2023). In the Monzón Valley (Huánuco, Perú), local producers process CCN51 cocoa following post-harvest practices that combine technical assistance with the ancestral knowledge of other cocoa-growing regions.

Primary Processing of Cocoa Beans

During fermentation, various yeasts, lactic acid bacteria, and acetic acid bacteria are involved in biochemical reactions that generate aroma, flavor and bioactive compounds, which are crucial for the quality and differentiation of cocoa in the chocolate industry (Barrientos et al., 2019; Ruiz-Santiago et al., 2024). Throughout this stage, total phenolic content, including anthocyanins, decreases, causing color changes that are characteristic of each fermentation method (Chávez-Salazar et al., 2023). Sensory attributes such as acidity, astringency and bitterness are also modulated by fermentation time, handling and microbial activity contributing to the final flavor profile of the cocoa beans (González et al., 2024).

Elsewhere, drying is a fundamental operation that affect physical, chemical and microbiological properties of cocoa beans, influencing their quality (Foster et al., 2024). For instance, parameters such as size, weight, and moisture content of the beans are key indicators to classify cocoa into quality grades (Sianipar, 2022). Color parameters are also affected by the drying method. Previous studies have reported significant differences in L*, a* and b* values between beans subjected to solar and artificial drying methods (Chávez-Salazar et al., 2023). Different drying technologies also influence the degradation of phenolic content as well as antioxidant capacity. In terms of sensory properties, oven drying tends to reduce overall quality, whereas solar drying has a lower impact (Sinuhaji et al., 2024).

To assess the quality of cocoa beans, rapid instrumental techniques such as Fourier-transform infrared (FT-IR) spectroscopy have been applied to identify their geographical origin, evaluate their authenticity or potential fraud (Teye et al., 2020) through multivariate analysis techniques, this provides support for a better interpretation of results with various applications in food science.

Multivariate analysis comprises a set of statistical methods that enable the simultaneous evaluation of multiple variables, facilitating the identification of complex patterns and correlations (Gil et al., 2019; Buvé et al., 2022). For instance, Cemin et al. (2022) evaluated the sensory descriptive attributes of chocolate using Principal component analysis (PCA). Similarly, Deus et al. (2020) used this technique for the classification of chocolates made from different cocoa clones. In addition, Hierarchical cluster analysis (HCA) has been used to detect adulteration in tea and coffee (Cebi et al., 2017) and in the typification of the origin, variety and roasting time of coffee beans (Guerrero-Peña et al., 2023).

Sensory characteristics such as flavor and aroma are key to the economic valuation of cocoa, which are normally evaluated by expert tasters. Desirable flavors include sweet and fruity notes, floral and citrus aromas, caramel and nutty flavors, and balanced bitterness; while undesirable compounds, when present in high concentrations, include acetic acid, lactic acid, and polyphenols (Llano et al., 2025). Traditionally, sensory evaluation relies on highly experienced panelists, which limits accessibility for small-scale producers or artisans due to the high costs associated with maintaining trained sensory panels. As an alternative, rapid descriptive methodologies adapted to consumer vocabulary and requiring fewer resources offer a more accessible and cost-effective solution (Pineau et al., 2022). Among these methods, the Flash Profile allows untrained judges (consumers) to generate sensory descriptors using their own vocabulary and subsequently classify them through sorting. This approach facilitates the development of sensory profiles that closely reflect consumer perception (Wang et al., 2022).

Given the influence of cultural practices, processing techniques, and environmental conditions on cocoa quality and market value, the aim of this study was to evaluate the effect of fermentation and drying practices on the physical, chemical-proximal and sensory characteristics of CCN51 cocoa beans (*Theobroma cacao*).

MATERIALS & METHODS

Cocoa Bean Processing

Cocoa beans were collected from 10 local producers in the Monzon Valley, located in Huánuco, Peru (9°16′47″ South, 76°23′46″ West), as indicated in Table 1. Harvesting, fermentation, and drying operations were monitored on-site at each producer's field between August and September 2020, in accordance with local agricultural practices. Regarding fermentation, it was conducted spontaneously in polypropylene sacks, each containing approximately 20 kg of wet beans. Drying was performed by spreading the beans on mats placed directly on the ground. An exception was Producer 3, who employed a solar dryer and manually turned the beans to promote uniformity. The dried fermented beans (DFBs), as well as cocoa fruits (CFs), were then packed in polypropylene bags and stored until analysis.

Analysis Methods

Physical and Color Characteristics

Weight of CFs (n=10) and DFBs (n=20) was determined by gravimetry; the number of seeds of CFs was determined by manual counting, according to recommendations by Rojas et al. (2020). Length (mm), diameter (mm), fruit color, external color (DFBE) and internal color (DFBI) were determined by image analysis employing photographs and using *ImageJ software®* (Best et al., 2020). Photos were obtained in JPEG format (3280x2460 114 pixels), using a CANON SX50 HS digital camera (CCD sensor, tripod 50cm above the lens, LED 115 light, 60Hz, 20W, color temperature: 6500° K (D_{65}) and

1050 lm at 45°angle using white A1 paper (90g x 24) as background. The RGB values were converted to the CIE L*a*b* scale. In addition, chromaticity (C*) and hue angle (h°) were calculated. The external color (DFBE) was measured from photos of the external surface of entire beans. For the internal color (DFBI), the beans were cut longitudinally. Additionally, the length (mm), width (mm) and thickness (mm) of the DFB were measured with a vernier (Litz professional 150 x 0.05mm) reported by Rojas et al. (2020).

Table 1: Location of cocoa producers CCN51 in UTM coordinates

Producers	Community	Planted area (ha)	UTM coordinates	
			East	North
Producer 01	Shitari	3.0	377103.0	8981130.0
Producer 02	Cachicoto	2.5	367404.0	8981445.0
Producer 03	Shianca	4.0	360540.0	8978286.0
Producer 04	El Carmen	2.0	355977.0	8979287.0
Producer 05	Camote	14.0	365594.0	8982983.0
Producer 06	Rio espino	2.0	368598.0	8981155.0
Producer 07	Manchuria	5.0	371074.0	8979873.0
Producer 08	Rio espino	10.0	369345.0	8981173.0
Producer 09	Rinconada	5.0	357898.0	8980451.0
Producer 10	Palo acero	2.0	380482.0	8978036.0

Determination of pH, Acidity and Proximate Composition

DFBs were characterized in terms of pH, acidity and moisture. pH was measured using a potentiometer (Schott) following the method 970.21 (AOAC, 2016). Titratable acidity was determined by 942.15 (AOAC, 2016). Moisture was carried out by drying in an oven (Memmert) following the method 931.04 AOAC (2016). Proximate chemical composition (protein, fat, ash, carbohydrates) of the DFB from the most representative producers (3, 4 and 5) according to multivariate analysis was determined according to AOAC (2019). In addition, a sample of the common variety (control) from the same Valley was used.

Total Phenolic Content (TPC)

The TPC of defatted samples of DFB from the 3 selected producers and a control sample were determined by the Folin-Ciocalteu method (Naczk & Shahidi, 1989) with some modifications. Samples (1g) were mixed with 15 mL of ethanol (50%) acidified with HCl (1%), though solvents such as methanol and acetone could be also used according to (Asiedu et al., 2025). The mixture was then stirred for 6 h and centrifuged at 6000rpm for 15min at 4°C. The supernatant was diluted (1/200), then 500µL was mixed with 250µL Folin-Ciocalteu 1 N and 1250µL of sodium carbonate 1.42 N. The reaction was incubated for 1 h under dark conditions and the absorbance was measured at 755nm using a spectrophotometer (Thermo Scientific, GENESIS 4001, USA). Finally, the results were expressed in milligrams of gallic acid equivalents per gram of the sample (mg galic acid eq. GAE/g.d.w.), calculated based on gallic acid calibration curve (concentration range of 0.005 to 0.035mg/mL; R^2= 0.999).

FT-IR Spectra Analysis

Spectral data of the selected DFB samples, previously ground and sieved (<250µm), along with the control sample, were obtained using a FT-IR spectrophotometer TruDefender FT (Ahura Scientific®, USA) coupled with an attenuated total reflectance (ATR) sampling accessory. Spectrum was collected in the wavenumber range of 4000 and 500cm^{-1}, with a resolution of 3cm^{-1}. Prior to each measurement, a background spectrum of ambient air was recorded, following the protocol described by Elderderi et al. (2020) and Villanueva et al. (2023).

Sensory Analysis: Flash Profile

Samples were prepared according to Streule et al. (2022) with slight modifications. The DFB from the producers, along with a sample of the common variety (control), were roasted over moderate heat (196.3±13.9°C) for 5minutes, then cooled and ground. In addition, a commercial sample of hot chocolate bar was considered, which was granulated and melted in a stove (FAITHFUL, GX-45BE) at 60°C for 15min inside pots with lids (polypropylene).

Eleven consumers (18 to 66 years old), with previous knowledge in cocoa and cocoa derivatives evaluation, were randomly recruited and instructed in the methodology, as recommended by (Rodríguez-Noriega et al., 2021). Sensory evaluation was carried out in 2 stages. In the first one, consumers were asked to generate characteristic sensory descriptors of the samples through observation, manipulation and tasting. In the second stage, consumers evaluated each descriptor previously generated using an ordinal scale for subsequent categorization (Puma-Isuiza & Núñez-Saavedra, 2020; Wang et al., 2022).

Data Analysis

A completely randomized design (CRD) was applied, where the factor under study was the cocoa producer, with ten levels (producers). Data on physical characteristics, colorimetry, proximate composition and TPC were analyzed using one-way ANOVA and Tukey's test (P<0.05). In addition, physicochemical characteristics of the DFBs were analyzed using multivariate analysis: PCA, HCA and Generalized Procrustes to select the most representative producers. All statistical analyses were performed using XLSTAT software version 2023.

RESULTS & DISCUSSION

Processing Conditions for Fermentation

Fermentation temperature monitoring revealed considerable variability, primarily influenced by local climatic conditions and the use of spontaneous fermentation (Table 2). Among the ten producers evaluated, five (1, 6, 7, 9, and 10) carried out fermentation for 5 to 7 days, aligning with the recommendations of Cardona et al. (2016). In contrast, three producers (2, 4 and 5) fermented their beans for only 3 days and two producers (3 and 8) for 4 days. These differences reflect a lack of standardization in fermentation practices among producers.

These results are consistent with the findings of Megias-Perez et al. (2020), who conducted spontaneous fermentation under stacking with the pulp in open-air piles in five countries (Brazil, Ecuador, Malaysia, Cameroon and Ivory Coast) with a duration between 120 and 168 hours (5 to 7 days), with periodic turning the first four days to

Table 2: Physical and chemical characteristics of CFs and DFBs from the 10 cocoa producers

Producer	CFs				Fermentation Conditions		Drying conditions		DFBs						
	Weight (g)	Length (mm)	Diameter (mm)	N° of seeds	Days	T (°C)	Day	T (°C)	Weight (g)	Length (mm)	Width (mm)	Thickness (mm)	pH	Acidity (%)	Moisture (%)
1	882.90±197.60^{a}	257.10±20.28^{a}	113.75±7.50^{a}	49.00±6.86^{a}	5	32.8±6.80^{a}	5	34.3±5.56^{cd}	1.61±0.21^{a}	23.77±1.83^{a}	13.27±0.79^{a}	9.71±1.12^{ab}	5.22±0.04^{bc}	2.28±0.16^{c}	7.68±0.10^{b}
2	890.40±156.20^{a}	256.12±21.95^{a}	116.30±10.09^{a}	48.30±9.01^{a}	3	32.9±9.61^{a}	4	41.9±3.88^{abc}	1.56±0.24^{ab}	23.52±1.92^{a}	13.82±2.26^{a}	9.59±1.30^{abc}	5.12±0.08^{bc}	3.73±0.22^{a}	6.70±0.24^{cde}
3	728.50±162.30^{a}	238.56±21.61^{a}	109.20±9.04^{a}	44.30±7.26^{a}	4	33.8±6.48^{a}	6	31.9±1.73^{d}	1.37±0.30^{b}	23.21±1.42^{a}	12.97±1.76^{a}	9.35±1.45^{abc}	5.39±0.03^{b}	3.61±0.10^{a}	6.26±0.13^{de}
4	941.70±181.00^{a}	258.49±25.08^{a}	115.92±9.59^{a}	46.10±5.13^{a}	3	30.8±6.07^{a}	4	34.0±1.18^{bcd}	1.46±0.23^{ab}	23.38±1.89^{a}	13.12±0.93^{a}	9.24±1.09^{abc}	5.14±0.06^{bc}	2.83±0.32^{c}	6.74±0.24^{cde}
5	915.80±190.30^{a}	263.67±14.43^{a}	114.07±5.55^{a}	49.70±5.01^{a}	3	30.2±8.13^{a}	4	35.5±6.16^{bcd}	1.51±0.25^{ab}	24.18±2.59^{a}	13.51±0.93^{a}	9.95±1.04^{a}	6.05±0.08^{a}	2.43±0.25^{c}	8.67±0.13^{a}
6	915.50±87.90^{a}	257.56±16.44^{a}	113.20±7.93^{a}	47.90±8.49^{a}	5	36.5±5.92^{a}	3	48.0±1.96^{a}	1.44±0.20^{ab}	24.39±1.73^{a}	13.07±0.63^{a}	8.64±0.87^{bc}	5.25±0.15^{bc}	3.55±0.22^{ab}	6.05±0.32^{e}
7	847.70±183.12^{a}	263.94±22.88^{a}	113.41±9.98^{a}	54.10±3.78^{a}	6	36.5±8.05^{a}	4	40.0±1.77^{abc}	1.55±0.20^{ab}	23.48±1.94^{a}	13.63±0.48^{a}	8.55±0.96^{c}	5.45±0.14^{b}	4.09±0.18^{a}	6.83±0.43^{cd}
8	901.60±172.40^{a}	255.46±19.13^{a}	117.04±3.31^{a}	48.80±9.35^{a}	4	30.9±6.05^{a}	4	42.8±5.07^{ab}	1.55±0.24^{ab}	23.25±2.08^{a}	13.46±0.69^{a}	9.07±1.15^{abc}	4.97±0.01^{c}	3.91±0.26^{a}	6.52±0.14^{cde}
9	766.50±114.90^{a}	266.24±17.02^{a}	111.88±6.37^{a}	53.30±4.11^{a}	5	33.4±4.91^{a}	4	41.5±2.87^{abc}	1.49±0.21^{ab}	23.68±1.52^{a}	12.91±0.95^{a}	8.71±0.86^{bc}	6.00±0.37^{a}	2.79±0.34^{c}	6.22±0.37^{de}
10	833.50±127.00^{a}	246.12±17.01^{a}	114.43±8.26^{a}	47.50±8.29^{a}	5	33.7±6.65^{a}	4	41.9±1.88^{abc}	1.44±0.19^{ab}	23.83±1.66^{a}	13.15±0.95^{a}	8.75±0.98^{bc}	5.43±0.03^{b}	2.90±0.19^{bc}	7.15±0.13^{bc}

Different letters within the same column indicate significant differences according to Tukey's test ($p < 0.05$)

promote homogeneity. No adverse effects on grain quality were observed, regardless of the country of origin, and the process resulted in favorable biochemical transformations that enhanced the sensory profile of the beans.

Other studies, such as those by Andrade et al. (2019), found similar traditional spontaneous fermentation systems, such as wooden or plastic boxes, mounds on open surfaces, and jute sacks. León-Roque et al. (2016) reported the use of fermentation boxes in the Peruvian regions of Piura, Cajamarca and Tumbes, maintaining a temperature close to 40°C with turning every 24 h for 6 days.

On the other hand, controlled fermentation alternatives have also shown promising results. For example, an optimal fermentation time of 155 hours (equivalent to 6.5 days) has been recommended by Mougang et al. (2024). In addition, Guillen-Guerrero and De la Rosa-Millán (2025) reported successful preservation of bioactive compounds at temperatures below 40°C, in contrast to 60°C, which favored carbohydrate–protein digestibility and enhanced the flavor profile. Similarly, the application of starter cultures has been shown to shorten fermentation time by 2 to 3 days while improving sensory attributes (Campos et al., 2025), particularly through the formation of flavor and aroma precursors that influence bean quality (Constante Catuto et al., 2024).

The duration of fermentation is a significant factor in the chemical profile of cocoa beans (Llano et al., 2025). According to Delgado-Ospina et al. (2022), this process depends on the cultivar, climate, type of fermenter, fruit ripeness, microbial load, duration of the anaerobic phase, and turning frequency. Spontaneous fermentations are associated with the presence of wild yeasts, lactic acid bacteria, and acetic acid, which vary depending on the region of origin at the stage of processing. Furthermore, the generation of by-products during fermentation has sparked interest in their utilization through the extraction of bioactive compounds (Domínguez-Pérez et al., 2020). However, extending fermentation beyond 6 days may reduce the sensory quality of cocoa beans due to the production of microbial metabolites.

In this study, it was identified that most producers in the Monzón Valley ferment cocoa in polypropylene bags for convenience, directly on the farm plots, regardless of bean quality. This is because buyers offer the same price for both types of fermented beans, without any economic incentive to differentiate quality, likely due to the lack of information and technical criteria in the local cocoa trade. However, technological changes (fermentation in drawers and protected solar dryers) and capacity building for cocoa farmers represent a challenge for sustainable production at this key stage.

Processing Conditions for Drying

The average temperature recorded during solar drying was 39.2°C, with a duration between 3 to 6 days (Table 2). This variability is influenced by the season, climate change, and the urgency of marketing. These findings coincide with those reported by Ackah and Dompey (2021), who recorded drying times (4 to 6 days) in rainy seasons, while Tejeda et al. (2024) applied a pre-drying for 24h followed by five days of traditional solar drying (30°C and 70% R.H.). For their part, Barrientos et al. (2019) used solar drying with plastic protection, with a duration of 132h (5.5 days), in thin layers, with a moisture content (7%) similar to the previous study. In contrast, Mougang et al. (2024) proposed an optimal protocol of 50.25°C for 45 hours (1.9 days) in a forced convection oven, considering it adequate to maintain grain quality.

However, it is important to avoid temperatures between 49.35 and 69.35°C due to the formation of acrylamides (Gil et al., 2020). This implementation, coupled with the high costs of controlled technologies, prevents producers from accessing them due to their high cost and the need to standardize the drying process.

Furthermore, drying plays an important role in reducing attributes such as astringency, bitterness, acidity, and the development of the brown color of the grains, associated with phenolic compounds (Cardona et al., 2016). However, variable environmental conditions are a challenge to achieve the humidity standard (7.0%), a critical attribute to ensure the absence of fungi that represent a risk of mycotoxin contamination that can compromise the quality of cocoa and its derivatives during manufacturing (Akinfala et al., 2020). The origin of these mycotoxins can begin on the farm, or come from the environment, soil, drying, or storage (Copetti et al., 2013). These primary production practices affect the quality of the beans required by the chocolate industry, affecting the standardization of its processes (Megias-Perez et al., 2020).

Physical and Colorimetric Characteristics of CFs and DFBs

The length, diameter, weight and number of seeds of the CF showed no differences between producers for the same type of cocoa (Table 2). However, in comparison to the Criollo and Trinitario varieties, Utrilla-Vázquez et al. (2020) reported lower values in weight (400.1 to 663.4 g), length (18.20 to 24.50cm), width (7.45 to 8.33cm) and seed number (28 to 35), demonstrating the influence of cocoa type on physical characteristics.

The weight and thickness of the DFB showed significant differences ($P<0.05$), while the length and width were similar. Andrade et al. (2019) reported comparable values for the same CCN51 clone from Ecuador and Peru: length (22.45 and 24.97mm), width (12.79 and 13.80mm), and thickness (8.24 and 9.78mm). According to the weight quality requirements established by INEN (2021), the cocoa beans could be classified as grade I. Furthermore, these dimensions are useful for predicting moisture content during storage (Barreiro & Sandoval, 2020), as well as for estimating mass and energy transfer flows required in artificial drying processes and equipment design.

The color of cocoa fruits (L^*, a^*, b^*, C^* and h) showed significant differences ($P<0.05$) among producers and the degree of maturity at harvest, due to the presence of reddish and yellowish fruits (Table 3) associated with the presence of metabolites such as flavonoids and carotenoids (Gallego et al., 2022). The effect of different degrees of maturity has been studied in three varieties (CCN51, ICS60 and EET8), reporting close colorimetric values for CCN51 (L^*= 44.93 to 50.63; a^*= 27.15 to 38.96; b^*=22.78 to 45.07) showing an increase of L^* and b^* as the maturity index (Soluble Solids/Titratable Acidity) increases in the mentioned specimens (García-Muñoz et al., 2021).

The dried beans exhibited variations in external coloration, with producer 5 showing the darkest beans ($L^*=30.64$) and producer 1 the lightest ($L^*=44.69$). The reddest beans corresponded to producers 9 and 6 ($a^*\approx14.60$). On the contrary, producer 5 presented a less reddish value ($a^*=5.99$). A directly proportional relationship of reddish color ($+a^*$) with fermentation temperature was observed under controlled pH conditions (Becerra et al., 2023) which coincides with producer 6 (36.5°C for 5 days). However, producer 7 with longer fermentation time (36°C for 6 days) did not manage to develop equally reddish beans.

The yellowest beans corresponded to producer 4 ($b^*=29.41$) and the lowest values were obtained by producers 5 and 7 ($b^*\approx5.50$). However, this trend differs internally since the darkest cocoa beans correspond to producer 5 (L^*= 22.70), while the reddest beans (a^*) report for producers 3 (7.38), 8 (7.36) and 10 (7.36). As for the b^* coordinate, the yellowest were producers 3 (2.88), 6 (2.66) and 7 (2.14). The values of the internal color coincide with the study of Ramos Escudero et al. (2021) of cocoa beans of white cultivars, Chuncho and CCN51 hybrids of commercial origin in the values of lightness L^* (16.82 to 44.46), chromaticity coordinates a^* (2.38 to 14.78) and b^*(1.23 to 8.47), hue h° (19.50 to 42.88) and chroma C^* (3.04 to 17.21).

It was observed that all chromatic parameters presented a reduction in relation to the external color, influenced by the fermentation and drying treatments. The highest color variation was recorded for producer 4 (ΔE= 35.42±4.48) and the lowest was for producer 5 (ΔE= 9.26±0.43). The characteristic brown coloration of cocoa beans develops during fermentation as a result of anthocyanin hydrolysis, which is induced by a decrease in pH. This degradation of pigments is accompanied by the formation of phenolic compounds and phlobaphenes, contributing to the final color of the beans (Ramos-Escudero et al., 2021; Becerra et al. 2023). According to ICONTEC (2024), well-fermented beans exhibit a brown or chocolate color, whereas poorly fermented beans exhibit a violet or violet-brown hue, and unfermented beans are characterized by a dark gray or violet color.

Regarding pH, values ranging from 5.12 to 5.45 were obtained for producers 2, 4, 1, 6, 3, 7 and 10, while producers 9 and 5 recorded a pH ≥ 6.00 and a pH below of 5.00 for producer 8. Andrade et al. (2019) evaluated the same variety from Peru reporting a pH range between 5.15 to 5.36, similar to those obtained in the first group. In this regard, Oliveira et al. (2021) indicated that a pH between 5.0 and 5.5 ensures the quality of the aromatic compounds, while a range of 4.0 to 4.5 results in lower quality of these compounds.

The acidity presented significant differences ($P<0.05$) located between the ranges 2.28 to 4.09% expressed in acetic acid, higher than expected and reported by Andrade et al. (2019) who found values in this same clone in Ecuador (0.63%) and Peru (2.05%). This difference in pH and acidity values is mainly attributed to the concentration of organic acids (Enaru et al., 2021).

Table 3: Colorimetric parameters (L*, a*, b*, C, and h°) of cocoa fruit (CF), external dried fermented bean (DFBE) and internal dried fermented bean (DFBI) of the 10 cocoa producers

Type of product	Producer	L*	a*	b*	C	h°
CF	1	35.30±7.46^{d}	34.81±8.01^{abc}	23.78±8.94^{ab}	42.44±10.83^{b}	33.83±6.58^{ab}
	2	44.75±6.41^{abc}	39.96±5.51$_{abc}$	28.15±9.56^{ab}	49.68±5.82^{ab}	34.71±10.25^{ab}
	3	42.65±6.61^{abcd}	36.34±6.31^{abc}	27.94±6.97^{ab}	46.19±7.29^{ab}	37.37±7.47^{ab}
	4	47.26±5.11^{ab}	41.42±4.55^{ab}	29.60±10.33^{ab}	51.69±6.16^{ab}	34.95±10.17^{ab}
	5	46.87±6.61^{ab}	34.89±8.55^{abc}	32.05±11.42^{ab}	48.67±8.04^{ab}	42.12±13.66^{a}
	6	40.33±6.61^{abcd}	30.27±7.38^{c}	24.86±10.15^{ab}	39.83±9.97^{b}	38.19±11.08^{ab}
	7	37.96±4.53^{bcd}	43.08±5.34^{a}	21.65±5.70^{b}	48.35±6.83^{ab}	26.40±4.35^{b}
	8	35.61±8.31^{cd}	36.94±9.17^{abc}	21.71±7.82^{b}	42.95±11.66^{b}	29.83±4.14^{ab}
	9	48.64±5.06^{a}	43.82±7.38^{a}	36.40±8.09^{a}	57.74±4.65$_{a}$	39.71±10.01^{ab}
	10	35.61±7.36^{cd}	32.45±7.17^{bc}	25.89±10.26^{ab}	42.55±7.73^{ab}	37.64±12.27^{ab}
DFBE	1	44.69±4.65^{a}	12.07±1.97^{abc}	23.12±4.66^{bc}	26.26±3.98^{bcd}	61.58±7.47^{ab}
	2	43.83±3.36^{ab}	11.19±2.01^{bcd}	20.48±5.91^{cd}	23.64±4.91^{cde}	59.64±10.42^{b}
	3	33.36±4.42^{d}	13.42±2.13^{ab}	15.48±6.76^{e}	20.83±5.96^{e}	46.63±10.61^{d}
	4	42.99±5.86^{ab}	10.68±3.15^{cd}	29.41±4.84^{a}	31.51±4.38^{a}	69.68±7.31^{a}
	5	30.64±2.76^{d}	5.99±1.62^{e}	5.88±2.54^{f}	8.55±2.52^{f}	43.25±11.72^{d}
	6	37.58±3.34^{c}	14.60±1.42^{a}	16.94±4.21^{de}	22.52±3.47^{de}	48.47±7.02^{cd}
	7	38.22±2.90^{c}	8.66±1.61^{d}	5.36±2.64^{f}	10.36±2.41^{f}	30.34±10.66^{e}
	8	41.22±3.60^{abc}	11.17±1.83^{bcd}	19.07±5.92^{cde}	22.48±4.56^{de}	57.67±11.88^{bc}
	9	42.69±4.05^{ab}	14.63±5.42^{a}	25.69±4.60^{ab}	30.19±3.38$_{ab}$	60.46±11.09^{ab}
	10	40.07±3.38^{bc}	12.33±1.77^{abc}	23.78±2.94^{bc}	26.90±2.43^{bc}	62.32±5.13^{ab}
DFBI	1	27.35±4.32^{ab}	5.87±1.22^{abc}	0.39±4.02^{a}	6.96±1.70^{abc}	-0.50±19.46^{a}
	2	25.61±3.46^{abc}	6.56±1.59^{bc}	0.14±2.43^{c}	6.96±1.70^{abc}	-0.50±19.46^{c}
	3	25.61±3.29^{abc}	7.38±1.67^{a}	2.88±3.28^{a}	8.27±2.77^{a}	17.44±16.07^{a}
	4	23.22±2.09^{c}	4.25±2.05^{c}	0.76±2.15^{a}	4.69±2.32^{c}	4.13±27.78^{b}
	5	22.70±2.96^{c}	5.09±1.48^{bc}	1.22±3.09^{b}	5.74±2.42^{bc}	6.88±23.12^{b}
	6	24.63±2.96^{bc}	6.69±1.74^{bc}	2.66±3.15^{a}	7.51±2.85^{ab}	16.69±16.50^{a}
	7	25.58±4.00	6.70±1.38^{bc}	2.14±3.05^{a}	7.49±2.07^{ab}	14.77±19.41^{a}
	8	25.58±5.40^{a}	7.36±1.60^{a}	2.06±3.35^{a}	8.18±2.18^{a}	13.59±20.35^{a}
	9	24.22±4.77^{cb}	6.64±1.95^{bc}	0.20±3.41^{c}	7.37±2.14^{ab}	-2.96±26.30^{c}
	10	25.29±3.08^{abc}	7.36±1.21^{a}	2.06±3.20^{a}	8.17±1.71^{a}	13.80±20.68^{a}

Different letters within the same column indicate significant differences among producers for each product type, according to Tukey's test ($P<0.05$).

The moisture content of DFBs from all producers complied with INACAL (2021) specifications, except for producer 5, which recorded a higher value (8.67%). According to ICONTEC (2024), only producer 10 (7.15%) approached the threshold for the *Premium cocoa* denomination. In contrast, producers 1(7.68%) and 5(8.67%) exceeded the 7.5% maximum limit, suggesting inadequate drying processes, which should be between 5 to 7 days. However, this time often depends on the climate of the production area (Andrade et al., 2019). According to INEN (2021), when moisture is less than 7%, the bean is brittle, and values above 8% moisture are leading to the development of molds (Akinfala et al., 2020). The physical and sensory characteristics, chemical composition and functional properties of cocoa beans depend on climatic factors, the crop variety and maturity of the fruit at the time of harvest, to which are subsequently added processing stages such as fermentation, drying and roasting (Herrera-Rocha et al., 2024).

Multivariate Analysis

The first two dimensions of PCA explained 59.82% of the total variability (Fig. 1B). With similar trends at 62% in the primary processing of fermentation studies (Haruna et al., 2024), which allowed the typing of the variables that contribute most to the variability between samples, differentiating cocoa between producers (Gil et al. 2019), it is considered a first option in the exploration of two-dimensional data (Buvé et al., 2022). The HCA (Fig. 1A) showed the formation of three clusters grouped by their similarity in physical, chemical, and colorimetric characteristics (cluster 1: producers 3, 10, 6, 8, and 7; cluster 2: producer 5; and cluster 3: producers 1, 2, 4, and 9), highlighting differences between producers according to their primary process presented among the dried cocoa beans (Gil et al. 2019). Of the three clusters formed from the PCA-HCA, producers 3, 4, and 5 were selected based on their squared cosine value ($Cos^2 > 0.6$) and the individual variance contributed in the first two dimensions of the PCA, which were subsequently analyzed for their proximate composition and total phenolic content (Table 3).

Proximate Chemical Composition of the Samples from the Selected Producers

The proximate chemical composition and total phenolic compound content (TPC) of the three producers and a control (Table 4) show significant differences among them ($P<0.05$). However, they are similar to those reported by Andrade et al. (2019) for the same cultivar, who obtained a protein content between 8.59 to 15.13%, fat from 50.31 to 54.28%, ash from 2.36 to 2.90% and carbohydrates from 32.18 to 34.22%. In addition, storage stages influence beans composition.

It was observed that the highest TPC was for producer 4 (140.65±1.66mg GAE/g.d.w.) and the lowest for producer 3 (114.34±1.08mg GAE/g.d.w.) and the control (111.50±0.71mg GAE/g.d.w.). The results are higher than those found by Borja Fajardo et al. (2022) for the same variety (95.41±2.50mg GAE/g.d.w.). Similarly, by Pedan et al. (2018) in a range of 44.51±0.90 to 106.77±5.21mg GAE/g.d.w. in different cocoa varieties. Albertini et al. (2015) mention that the initial TPC concentration of cocoa beans is variable and is attributed to factors such as variety, geographical characteristics, maturity and harvest time. Subsequently, this value decreases as a consequence of the fermentation, drying and roasting process (Stanley et al., 2018; Cortez et al., 2023; Herrera-Rocha et al., 2024).

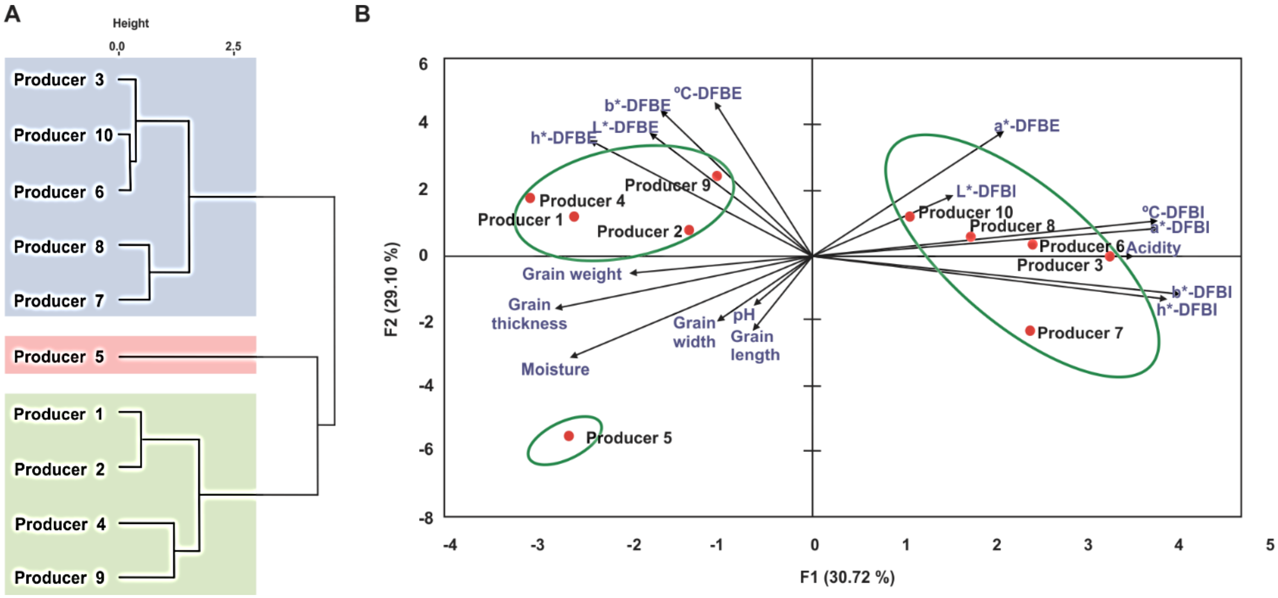

Fig. 1: (A) Hierarchical Cluster Analysis performed on the physical, chemical and colorimetric characteristics of the 10 cocoa producers. (B) Principal Component Analysis based on physical (length, width, thickness, weight), chemical (moisture, pH), and colorimetric (L*, a*, b*, h, and °C) parameters of the external (DFBE) and internal (DFBI) portions of the cocoa beans.

FT-IR Spectrum

The mid-infrared spectrum (FT-MIR) of cocoa samples from the 3 selected producers and the control sample are shown in Fig. 2. In the region comprising 3600 and 3200cm^{-1}, absorption peaks corresponding to hydroxyl (-OH) groups were observed, which are associated with water content. The intensity of these peaks was highest for producer 4 (5.13%) and lowest for producer 3 (4.5%), consistent with the findings of Johnson et al. (2023). The bands of the -CH functional groups (3200 and 2700cm^{-1}) corresponding to the carbon chain of triglycerides (Bresson et al., 2021) showed a predominant peak for the common variety associated with the fatty its higher fat content (54.85%). The region between 1800 and 1700cm^{-1} displayed peaks characteristic of carbonyl (C=O) groups, typically associated with lipid and protein structures. Moreover, a remarkable variability for the control and producer 4 is observed in the fingerprint region (1500-600cm^{-1}) (Bresson et al. 2021). In the phenol group region (1390 to 1317cm^{-1}), slightly different bands associated with phenolic compounds can be appreciated (Johnson et al., 2023) with producers 4 and 5 standing out.

Flash Profile

The results of the *Flash* Profile (Fig. 3) show the sensory characterization made by consumers in which 3 clusters are identified: The hot chocolate bar is characterized by a predominance of sweet, cinnamon flavor and a lesser dark brown color. Cocoa from producers 3 and 5 have similar characteristics of dark brown color, roasted smell, burnt smell, roasted aroma, flavors (bitter, roasted and burnt), sandy texture typical of roasted cocoa beans. Likewise, the sample from producer 4 and the common variety (control) showed similarities with a predominance of dark brown, grainy, earthy texture, bitter, astringent, with a shine associated with the fat content, cocoa flavor, but without the presence of the smell and burnt flavor particular to roasted nibs.

The samples under analysis were mainly characterized by their bitterness, which was in agreement with that reported by Streule et al. (2022) who in a quantitative descriptive analysis with trained judges identified bitterness associated with the presence of polyphenols present in cocoa as descriptors. Bitter taste in cocoa and chocolate specifically may result from the presence of methylxanthines, such as theobromine and caffeine, as well as flavonoids with relatively low molecular weight, including the flavan-3-ols epicatechin, its epimer catechin and some oligomers (Stark et al., 2006). Some of these compounds are affected by cocoa variety, growing conditions, season, maturity at harvest and land postharvest processing such as fermentation and roasting (Aprotosoaie et al., 2016; Kongor et al., 2016; Lemarcq et al., 2020; Gaspar et al., 2021).

The presence of a burnt odor/taste is attributed to deviations in direct-fire roasting, which affects the quality of the beans, highlighting the importance of using a proper roaster. McClure et al. (2022) determined that higher roasting (i.e., higher temperatures and longer time) results in a decrease in bitterness, because bitter and astringent compounds such as flavan-3-ols epicatechin and procyanidin B2 were substantially reduced during the roasting process. In addition, the reduction of the particle size of the samples exposed to heat adopts an earthy texture that could attribute possible defects and the

Table 4: Results of proximate analysis and TPC of DFB on a dry basis

Samples	Protein (%)	Fat (%)	Ash (%)	Carbohydrates (%)	TPC (mg GAE/g.d.w.)
Control	13.48±0.06^{a}	54.85±0.04^{a}	2.84±0.02^{c}	28.84±0.12^{d}	111.50±0.71^{c}
Producer 3	12.56±0.13^{c}	44.99±0.01^{d}	3.05±0.01^{b}	39.40±0.09^{a}	114.34±1.08^{c}
Producer 4	13.16±0.07^{b}	48.74±0.07^{b}	3.65±0.00^{a}	34.46±0.15^{c}	140.65±1.66^{a}
Producer 5	12.93±0.13^{bc}	46.75±0.09^{c}	2.71±0.03^{d}	37.62±0.22^{b}	135.98±1.19^{b}

Different letters within the same column indicate significant differences according to Tukey's test (P<0.05).

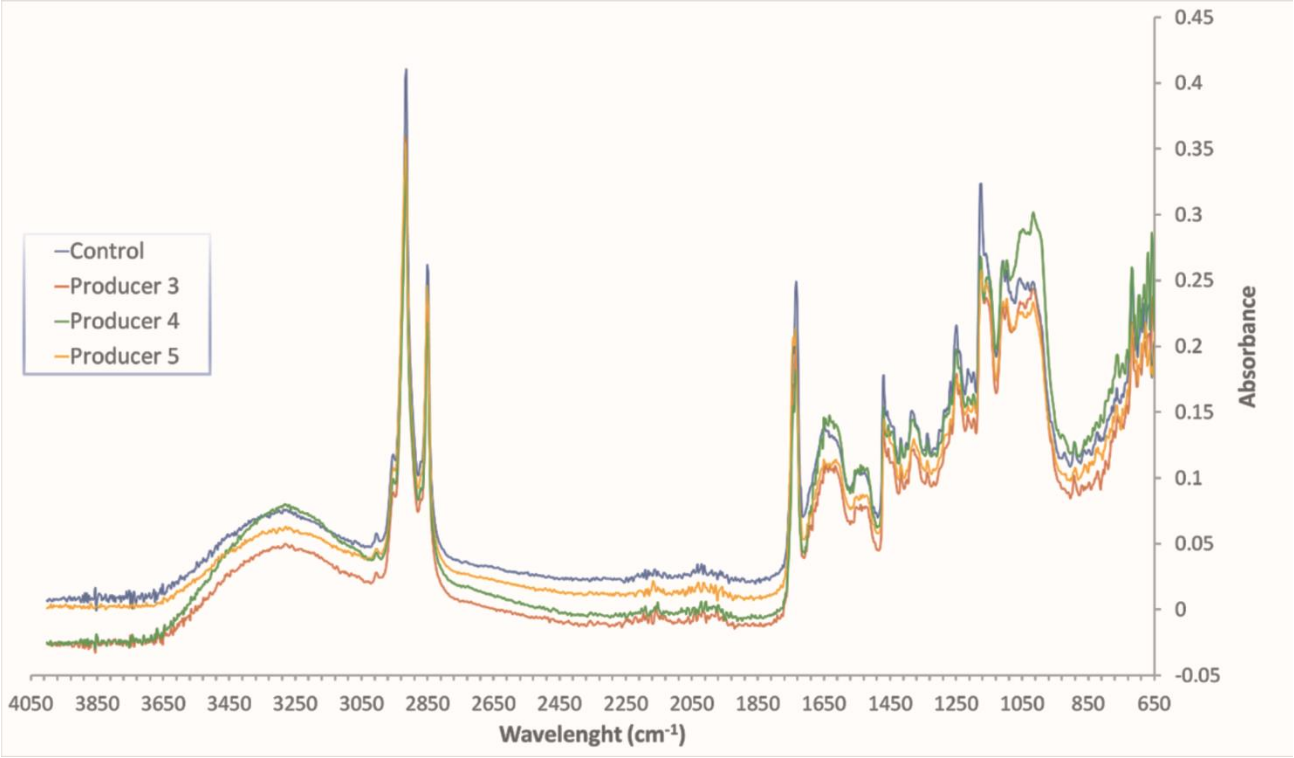

Fig. 2: Mid-infrared (FT-IR) spectra of the DFB by producers and control (common variety).

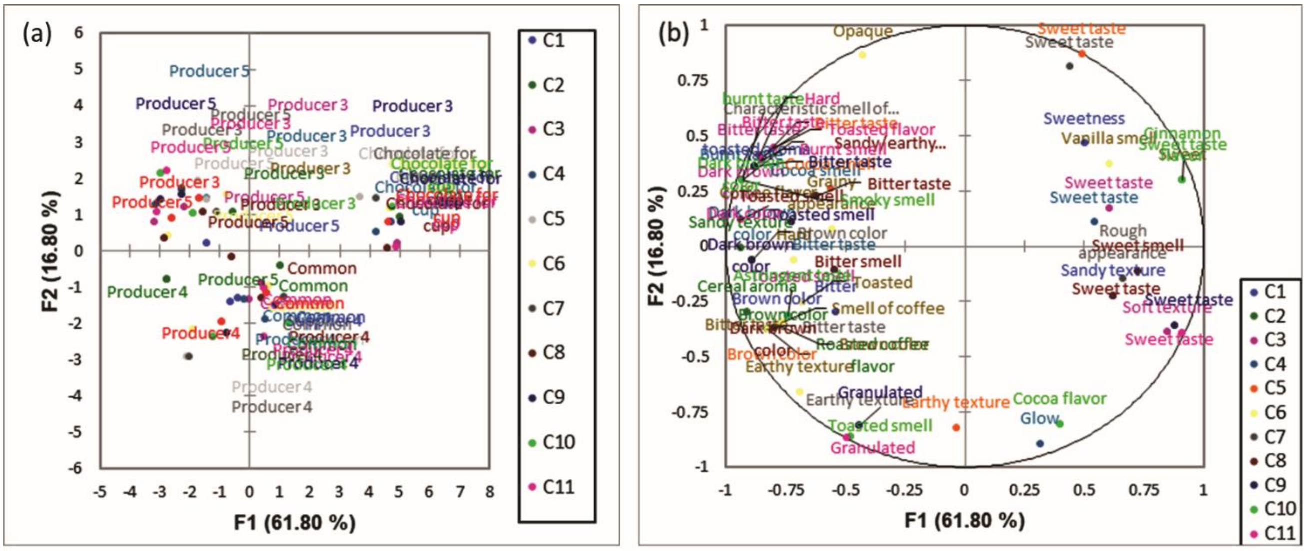

Fig. 3: Consensus samples (a) and sensory attributes by consumers (b). C1 - C11: consumers.

The presence of a burnt odor/taste is attributed to deviations in direct-fire roasting, which affects the quality of the beans, highlighting the importance of using a proper roaster. McClure et al. (2022) determined that higher roasting (i.e., higher temperatures and longer time) results in a decrease in bitterness, because bitter and astringent compounds such as flavan-3-ols epicatechin and procyanidin B2 were substantially reduced during the roasting process. In addition, the reduction of the particle size of the samples exposed to heat adopts an earthy texture that could attribute possible defects and the formation of the dark brown color, characteristic of cocoa nibs. Barrientos et al. (2019) evaluated the sensory characteristics, before and after cocoa fermentation, observing an increase in the floral and milky odor descriptors, as well as acid, nutty, fruit, fat, cocoa, body and viscosity attributes; similar to those reported by Menezes et al. (2016) who have observed that there is a positive correlation between the level of fermentation and the expression of floral, fruity and sweet aromas, decreasing bitter taste, as well as tobacco, spicy, raw/green and sweet panela flavors, at the end of fermentation. It should be noted that primary processing (fermentation and drying) is a cultural practice applied by producers by ancestral tradition, where the fermentation time (days), drying method and geographical origin, contribute to the flavor and aroma of the chocolate (Cardona et al., 2016; Nguyen et al., 2022) and which variability in these working methods can affect the commercial quality required by the external market.

The spontaneous fermentation (30.2 to 36.5°C) and solar drying (34.0 to 48.0°C) practices of the 10 producers showed heterogeneity. Cocoa fruits were similar in all physical characteristics (length, diameter, weight, number of seeds), while DFB differed in weight and thickness ($P<0.05$). Fruit colorimetric parameters influenced the chromaticity of external and internal cocoa bean color (8.55 to 31.51 and 4.69 to 8.18) and hue angle (29.11 to 69.68 and -0.50 to 17.44). Principal component and hierarchical cluster analysis identified three groups of producers with differences in proximate composition, phenolic compounds and FT-IR spectra that typify their origin. In turn, the *flash* profile identified producer 4 as similar to the common variety but different from hot chocolate bar (third group) due to its chemical composition. This study reveals heterogeneity in fermentation and drying practices among local producers of Monzon Valley in Peru. Despite, it led on identify producers of standard cocoa quality.

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Data Availability: Supporting data not included in the manuscript are available from the corresponding author upon request.

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Author's Contribution: This study was a collaborative effort among all authors. Dino Joe Flores coordinated logistics, designed the methodology, and contributed to writing, Tarsila Tuesta participated in writing and reviewing. Jhoselyn Liñan-Pérez participated in methodology and writing, Gustavo Puma-Isuiza and Reynaldo Silva-Paz conducted data analysis and contributed to writing. Oscar Jordán-Suárez was involved in methodology, writing, reviewing and editing; Miriam E. Ramos Ramírez contributed in the methodology, writing, reviewing and editing. All authors reviewed and approved the final manuscript.

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