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Physicochemical Characteristics of Cocoa Butter from Central Sulawesi, Indonesia

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ABSTRACT

Cocoa butter characteristics vary between origin, therefore influencing its industrial quality and application. This study investigated physicochemical characteristics of cocoa butter from eight districts in Central Sulawesi, Indonesia. Cocoa butter was extracted with a hydraulic press and analyzed for free fatty acids (FFA), moisture content (MC), slip melting point (SMP), fatty acids profile using GC-FID, triacylglycerol profile using HPLC-RID and solid fat content (SFC) profile convert from DSC melting curve. Data were analyzed using one-way ANOVA (p<0.05), followed by Tukey's HSD test for multiple comparisons. Principal component analysis (PCA) was performed to identify geographic clustering patterns. Significant differences were observed across districts. Samples FFA were complied with the Indonesian, CODEX, and industry standard, except cocoa butter from BG. Major fatty acids were detected, such as palmitic (24.08–27.42%), stearic (27.78–35.37%), oleic (32.48–40.45%), as well as major triacylglycerol such as POP (14.87–18.55%), POS (40.91–43.37%) and SOS (27.28–31.42%). Slip melting point range from 29.5–32.22 °C. Butter contain 60.8–74.3% solid fraction at 20 °C, then rapid melting to 30 °C. Strong positive correlation was found between FFA, UFA, and MUFA. Conversely, those variable correlate negatively with SFA, SFC 25 °C, and SMP. PCA revealed four geographic clusters which show that geographic origin influence variation in fatty acid composition, triacylglycerol profile, and melting behavior. These findings show distinct regional profiles and confirm Central Sulawesi's potential as a source of high-quality cocoa butter for industrial applications.

Keywords: Central Sulawesi, cocoa butter, fatty acid, melting, solid fat content, triglyceride

INTRODUCTION

Cocoa butter, derived from cacao beans (*Theobroma cacao* L.), is highly valuable due to its demand as raw materials in food industries (e.g chocolate and confectionery, bakery, etc.) (Loke *et al*., 2024). The global demand of cocoa butter continues to increased, supporting significant market growth projections for the coming years (Shavez Beg *et al.,* 2017). To manage the challenge of high demand but limited supply, the industry must source cocoa butter from variety of origins to maintain production capacities (Beckett *et al.,* 2017; Sirbu *et al.,* 2018). Indonesia produce 650.6 thousand tons of cacao beans, ranking as one of the world's largest suppliers alongside Ivory Coast and Ghana (BPS, 2023). Furthermore, reports from the Ministry of Agriculture in 2022 noted that Indonesia's export contribution reached 12.5% of the world's total cocoa butter exports. Therefore, the combination of high pro-duction volume and established export markets underscores Indonesia's significant potential as a supplier of high-quality cocoa butter. However, high production volume does not guarantee uniform butter quality, because variations in geographic origin and post-harvest practices may significantly affect physicochemical properties relevant to industrial processing.

One of the unique attributes of cocoa butter is its solid and brittle texture at room temperature (20–25 °C) and then fast melting just below the body tem-perature (37 °C) (Afoakwa, 2016). This uniqueness is largely determined by the types of fatty acids present and their positional distribution within triacylglycerol (TAG) molecules (Buscato *et al.,* 2017). Symmetrical TAGs or (saturated-unsaturated-saturated) SUS group account for approximately 79–89% of the predominant TAG species in cocoa butter. It primarily consists of palmitic, stearic, and the oleic acid that occupies the sn-2 position forming the POS, SOS, and POP molecules (Yao *et al.,* 2020). Previous studies have shown that the proportion of TAG such as monounsaturated (SUS) type correlated with higher melting point (Ribeiro *et al.,* 2012). Moreover, the solid fat content (SFC) profile of cocoa butter

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reflects its thermal behavior, showing hardness below 25 °C, resistance to heating between 25 and 30 °C, and pronounced melting within 27–33 °C, and after 35 °C melts completely (Norazlina *et al.,* 2023). According to Vieira *et al.* (2015), the difference in SFC values between temperature point of 25 to 35 °C is used by industries to assess cocoa butter melting properties. The larger the differences, the harder the fat is and the decrease of solids goes more slowly.

Several factors affect the cocoa butter composition and thus its melting properties. Studies have shown that growing environment (climate, sunlight exposure, altitude and rainfall) (Chaiseri and Dimick, 1989; Firmanto *et al.,* 2019; Hatmi *et al.,* 2021; Houphouet *et al.,* 2023; Mustiga *et al.,* 2019; Vieira *et al.,* 2015) and postharvest processing (harvesting, fermentation, and drying) (Chumthong *et al.,* 2024; Servent *et al.,* 2018; Sirbu *et al.,* 2018) of cacao beans as raw materials remarkably influence the cocoa butter characteristics. It was previously suggested, hard cocoa butter mostly from countries with warmer climate or close to the equator such as Indonesia, contains high proportion of SUS group TAG (POS, SOS, POP), thus has higher melting point (Firmanto *et al.,* 2019; Marty-Terrade and Marangoni, 2012). Softer cocoa butter is avoided by chocolate industries because it could cause excessive softness, prone to fat bloom formation, inefficiency at tempering stage and phase incompatibility (Ribeiro *et al.,* 2012; Vieira *et al.,* 2015). Fully fermented and dried cacao beans maximize cocoa butter extraction yield (Chun Lin and Meng Choong, 2022), but geographic origin has a stronger influence on butter composition than fermentation duration itself (Sirbu *et al.,* 2018). Blending cocoa butter from different origin which have different characteristics, could cause inconsistency in final products quality.

Central Sulawesi province has the largest cocoa plantations area, covering approximately 274.003 thousand hectares in 2022, or 19.28% of the total national cocoa plantations area (BPS, 2023). The differences in geographic, climate and post-harvest techniques between each plantation could contribute to the variation in cocoa butter characteristics. Recent studies of Indonesian cocoa butter mainly focus on how fatty acids composition vary between each region (Firmanto *et al.,* 2019; Hatmi *et al.,* 2021; Ristanti *et al.,* 2016). However, the characterization and comparative analysis on triacylglycerol composition and melting profile has not yet completely explored, particularly for cocoa butter from Central Sulawesi. These physicochemical characteristics are important to determine cocoa butter hardness, thermal stability, tempering behavior and compatibility in chocolate manufacturing and fat blending applications. Whereas, research-based studies are needed to evaluate and assess current cacao processing chain practices in order to improve the down-stream program in Central Sulawesi. For this reason, the purpose of this study was to investigate how origin affects the quality and characteristics of cocoa butter. We have sampled fermented cacao beans originate from 8 districts in Central Sulawesi and was processed to obtain cocoa butter in local cacao processing facility. The effects of geographic origins on moisture content (MC), free fatty acid (FFA), slip melting point (SMP), fatty acids composition (FA), triacylglycerol (TAG), and solid fat content (SFC) were analyzed and compared. To our knowledge, this is the first comprehensive report that links cocoa butter fatty acids and triacylglycerol profile directly with their melting properties from eight districts of a single province in Indonesia.

MATERIALS AND METHOD

Materials

Materials used in this study included fermented and dried cacao beans from *Forastero* group which then processed into cocoa butter. Titration reagents such as ethanol (Emsure, Germany), sodium hydroxide (Emsure, Germany), and phenolphthalein indicator (ACS Reagent, US) were used. Chromatographic solvents and preparation agents such as hexane (Emsure, Germany), methanol (Emsure, Germany), boron trifluoride in methanol (Merck, Germany), sodium chloride (Emsure, Germany), anhydrous sodium sulfate (Merck, Germany), acetone (Emsure, Germany), acetonitrile (Emsure, Germany), and chloroform (Emsure, Germany). Analytical standards were margaric acid (Sigma-Aldrich, US), fatty acid methyl ester (FAME) mix standard (Supelco, US), and triacylglycerol standards (Supelco, US) were used. Liquid nitrogen was utilized to maintain the cooling process during thermal analysis.

Cacao sampling and cocoa butter extraction

Cacao beans cultivated from eight different districts in Central Sulawesi include Sigi (SG), Banggai (BG), Toli-toli (TL), Buol (BU), Poso (PO), Parigi Moutong (PM), Morowali Utara (MU) and Donggala (DG) were sampled. The sampling strategy aimed to cover the main cacao-producing smallholder regions of Central Sulawesi (Figure 1). Simple random sampling technique was utilized. In accordance with regional post-harvest practice, cacao beans were fermented and dried to meet the standard moisture of ≤7.5%. The cacao beans were distributed to the cocoa processing facility manage by local government.

Cocoa butter extraction using the pressing technique refers to Vieira *et al.* (2016) with slight modifications. Each sample (5 kg of bean) was processed in duplicate. It was sorted and then roasted for 30 min at a temperature of 100 °C. The roasted beans then put into a winnowing unit to separate the shell from the cocoa nib. Cocoa nibs were crushed to produce cocoa mass. The automatic hydraulic type press NACHI IP Pump IPH-48-20-20 (LASINKA, ICCRI, Indonesia) was conditioned at a temperature 60 °C. Cocoa mass of ±1.5 kg was pressed at a pressure of 3000 Psi for ±25 min. The liquid cocoa butter was filtered with a nylon filter to reduce the cocoa solids incorporation. The yield of raw cocoa butter was collected separately, packed in a clean and secured container, cooled to room temperature, then stored in a closed container at a temperature below -20 °C.

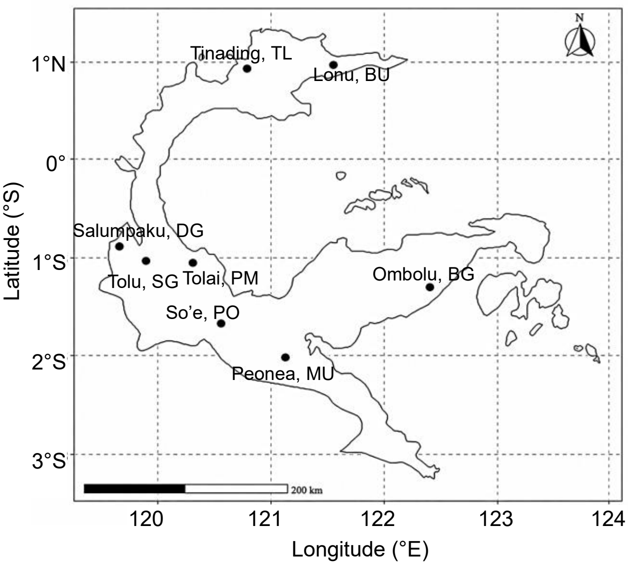

Figure 1. Geographic regional map of sampled cacao beans origin from 8 districts in Central Sulawesi. SG= Sigi, BG= Banggai, TL= Toli-toli, BU= Buol, PO= Poso, PM= Parigi Moutong, MU= Morowali Utara, and DG= Donggala

Moisture content and free fatty acid

Analyses of moisture content (MC) and free fatty acids (FFA) of samples were carried out according to in AOCS Ca 2c-25 (2017) and AOCS Ca 5a-40 (2009), respectively. Analyses were performed in triplicate for each sample.

Fatty acid composition

For each cocoa butter sample, fatty acid methyl esters (FAMEs) were prepared using the AOAC official method 948.22 technique (Torres-Moreno *et al.,* 2015). Gas chromatography (GC) instrument (7890A, Agilent Technologies, USA) equipped with a flame ionization detector was used to analyze the fatty acid profile in accordance with Taufik *et al.* (2016). A polar capillary column DB23 (60 m length, 0.25 mm internal diameter, 0.25 μm film thickness) was used at a column pressure of 10 psi. The initial column oven temperature was set at 130 °C for 2 min, and programmed to increase to 170 °C at 6.5 °C/min for 5 min, 2.75 °C/min up to 215 °C for 12 min, and 30 °C/min up to 230 °C for 28 min. Injection volume was 1 μL and used helium gas as the carrier phase. Peaks were identified by comparing retention times with known FAME standards. Quantification of fatty acid profiles was calculated from peak areas, expressed as a percentage of the total chromatogram area.

Triacylglycerol composition

The triacylglycerol (TAG) profile of cocoa butter was assessed following AOCS official method Ce 5b-89 using high-performance liquid chromatography (HPLC) equipped with a refractive index detector (1200 series, Agilent, USA) (Norazlina *et al.,* 2024). A Zorbax Eclipse XDB C-18 (250x4.6 mm, Agilent Technologies Inc., USA) column in series with Microsorb MV (250x4.6 mm, Rainin Instrument Co. Inc., USA) column was used for the analysis. Slight modification applied to the acetone and acetonitrile (85:15, v/v) as mobile phase. Prior to injection, each sample was dissolved in acetone:chloroform (2:1, v/v) in order to obtain 5% concentration. Flow rate set to 0.8 mL/min, pressure 8 to 9 mPa, and detector (RID) temperature of 35 °C. The injection volume was 20 μL and was run for 60 min TAG composition was expressed as percentage concentration and identified by comparing chromatographic retention times with TAG standards.

Slip melting point

Slip melting point (SMP) was analyzed by the open capillary tube method following the AOCS official method Cc 3b-92 (Norazlina *et al.,* 2022). Cocoa butter was heated to liquid fraction and filled into capillary tubes for 10 mm length. The capillary tubes were cooled to at 4–10 °C for 16 h. Capillary tube was tied to thermometer and dipped into 10 °C of water. Sample was heated slowly with 1 °C increase/min and agitated with magnetic stirrer (IKA RCT Basic, Germany). SMP represents the temperature at which butter in capillary tube immersed in water becomes soft enough to slip and move upward within the tube. Analyses were performed in triplicate for each sample.

Solid fat content

Cocoa butter samples were analyzed using differential scanning calorimetry (DSC) (Shimadzu DSC 60, Japan) according to AOCS official method Cj 1-94 (Norazlina *et al.,* 2023). The slight modification was applied to the temperature programs which is rapidly heating from 26 to 80 °C, held for 10 min, then cooling to -50 °C at 10 °C/min, held for 10 min, followed by heating at 5 °C /min to +90 °C. Liquid nitrogen was used to help maintain the cooling process. DSC data were acquired using TW-60 software (Shimadzu, Japan), including determination of melting temperature ranges and enthalpy values. Solid fat content (SFC) was quantified by calculating the partial areas of the thermograms correlated with solids percentages (Devi and Khatkar, 2017).

Statistical analysis

The experimental data were analyzed through one-way ANOVA using SPSS version 25 (IBM, USA) to determine the effect of geographic origin on cocoa butter characteristics. When overall differences were significant (p<0.05), Tukey's HSD was applied for pairwise mean comparisons. The analysis was carried out with two replications. Additionally, principal component analysis (PCA) was generated using R (R Foundation for Statistical Computing, Austria) (R Core Team, 2024) and RStudio IDE (Posit Software, PBC, USA) (RStudio Team, 2023) to reduce multiple variables into two principal components (Sari *et al.,* 2025) and to establish geographical clustering.

RESULTS AND DISCUSSION

Cocoa butter color, moisture, and free fatty acid content

Extracted cocoa butter appears as a pale-yellow solid at room temperature. This color is typical for raw unrefined cocoa butter, which retains some of the natural pigments from the cacao beans (Afoakwa, 2016). Cocoa butter transforms into a liquid that has an amber hue or golden yellow color when melted. This change occurs due to the alteration in light absorption properties as the fat transitions from a solid crystalline structure to a fluid state. As shown in Figure 2, extracted cocoa butter from each district can be visually distinguish by its color. Cocoa butter from MU, BU, and DG has an intense yellowish brightness. Cocoa butter from TL is brownish yellow, while PO is reddish yellow. Cocoa butter from BG, SG, and PM exhibits a dull yellow color. According to Sari *et al.* (2025), the color of cocoa butter is developed during stages of processing. In addition, deodorized cocoa butter is pale yellow and uniform in color compare to undeodorized cocoa butter (Ramlah and Lullung, 2018). However, the samples used in this study were raw fats without any refining process. Furthermore, fully fermented beans, such as cocoa beans from TL, produce fats with a higher fat-soluble pigment content than unfermented beans (Firmanto and Muhammadiyah, 2018), which we assumed that could lead to differences in color.

Table 1 showed the moisture content (MC) and free fatty acid (FFA) of cocoa butter from each of the district. Results showed significant differences in (p<0.05) MC and FFA value of cocoa butter from different origin. MC and FFA of cocoa butter from Central Sulawesi were in range of 0.12–0.25 and 0.59–2.87% (oleic acid), respectively. Sample from PM district had the lowest MC and FFA. Meanwhile, cocoa butter from PO, SG, and MU exceeded the standard limit according to Indonesian Nasional Standard which is 0.2%. The MC in cocoa butter depends on the MC of cocoa liquor after grinding stage (Venter *et al.,* 2007). This finding is consistent with earlier reports that butter from fully fermented and properly dried beans meets moisture specifications, whereas under-fermented beans yield higher-moisture butter.

Table 1. Moisture content and free fatty acids of cocoa butter from eight districts in Central Sulawesi

Sample	MC (%)	FFA (% Oleic Acid)
BG	0.17±0.01^{ab}	2.87±0.36^{d}
TL	0.18±0.02^{ab}	0.89±0.04^{c}
PO	0.22±0.02^{bc}	0.74±0.03^{abc}
SG	0.25±0.02^{c}	0.83±0.00^{bc}
MU	0.21±0.02^{bc}	0.62±0.10^{ab}
BU	0.18±0.02^{ab}	0.80±0.01^{abc}
DG	0.20±0.02^{bc}	0.91±0.02^{c}
PM	0.14±0.01^{a}	0.59±0.02^{a}

Note: Values expressed as means ± standard deviation of the replications. Numbers in the same column and followed by the same letter show no significant difference based on Tukey HSD test at 5% of significance. FFA= free fatty acids, MC= moisture content. SG= Sigi, BG= Banggai, TL= Toli-toli, BU= Buol, PO= Poso, PM= Parigi Moutong, MU= Morowali Utara, and DG= Donggala

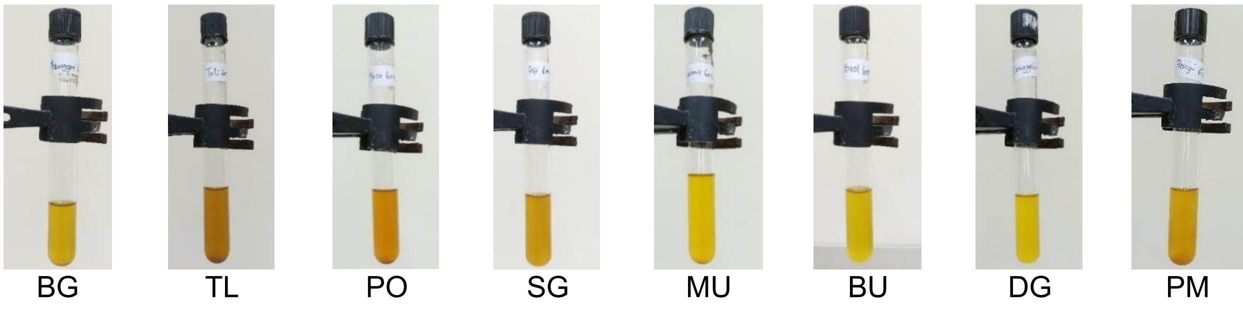

Figure 2. Appearance of cocoa butter, melted completely at 50 °C, from eight districts in Central Sulawesi. Noticeable differences in color (yellowish to brownish) suggest variations in post-harvest practices and bean quality that may influence physicochemical properties

All the FFA values complied with the Indonesian and CODEX standards (1.75%) (FAO/WHO, 2001), except for cocoa butter from BG, which showed a significantly higher FFA level compared to the others. This result aligned with expectations, as the beans from BG, although fermented, had undergone long and improper storage, which led to mold growth (Figure 3). Cacao beans contain endogenous lipase that become active during pod storage (Alhassan *et al.,* 2024). Moreover, it can also be produced by microorganisms such as fungi, which are commonly found in moldy beans resulting from poor post-harvest practices, including inadequate drying, improper fermentation, and unsuitable storage conditions (Tape *et al.,* 2023). It can catalyze the hydrolysis of triglycerides, converting them into free fatty acids and glycerol. Higher levels of FFAs in cocoa butter are undesirable for both producers and chocolate manufacturers, as they can lead to a reduction in the quality of fermented cacao beans and a decrease in the hardness of the cocoa butter (Müller and Careglio, 2018). According to Guehi *et al.* (2008), healthy beans contain FFA from 0.2 to 0.8%, meanwhile beans that are clustered and black contains much higher FFA (10%). Houphouet *et al.* (2023) reported that FFA levels were varied between each region of origin, but our result showed that the beans condition had a greater influence on the butter quality.

Fatty acids profile

The fatty acids profile of cocoa butter originates from eight plantations in Central Sulawesi significantly different (p<0,05) between districts. As shown in Table 2, each cocoa butter contains variation of palmitic (C16:0), palmitoleic (C16:1), stearic (C18:0), oleic (C18:1), linoleic (C18:2) and α-linolenic (C18:3) acids. Minor amount of myristic (C14:0), pentadecanoic (C15:0), margaric (C17:0), arachidic (C20:0), gadoleic (C20:1) and behenic acid (22:0) also present, in line with previous studies reported by Figueira and Luccas (2022), Ristanti *et al.* (2016), and Vieira *et al.* (2015). The levels of palmitic (26.3 to 29.20%), stearic (32.14 to 34.61%), oleic (32.87 to 33.25%), linoleic (1.74 to 2.30%), and arachidic (1.69 to 1.92 %) acids in cacao beans from Central Sulawesi have been reported by Firmanto *et al.* (2019), which align with the findings of this study.

A

B

Figure 3. Comparison between fermented moldy beans from BG, marked in red circle, and normal bean from MU. Mold contamination in BG beans is linked to elevated FFA levels in the cocoa butter. A= BG (Banggai), B= MU (Morowali Utara)

Tabel 2. Fatty acids (FA) composition of cocoa butter from 8 districts in Central Sulawesi

FA (%)	Districts							
	SG	BG	TL	PO	MU	DG	PM	BU
C14:0	0.09 ± 0.00^{c}	0.09 ± 0.00^{c}	0.06 ± 0.00^{a}	0.09 ± 0.00^{bc}	0.08 ± 0.00^{bc}	0.09 ± 0.00^{c}	0.08 ± 0.00^{b}	0.05 ± 0.00^{a}
C15:0	0.03 ± 0.00^{bc}	0.03 ± 0.00^{c}	0.03 ± 0.00^{bc}	0.03 ± 0.00^{bc}	0.03 ± 0.00^{bc}	0.03 ± 0.00^{bc}	0.01 ± 0.02^{ab}	0.00 ± 0.00^{a}
C16:0	27.42 ± 0.01^{b}	25.82 ± 0.26^{ab}	26.02 ± 1.61^{ab}	24.08 ± 0.01^{a}	25.02 ± 1.73^{ab}	24.34 ± 0.68^{a}	24.45 ± 0.19^{a}	25.05 ± 0.51^{ab}
C16:1	0.28 ± 0.01^{b}	0.24 ± 0.03^{ab}	0.24 ± 0.02^{ab}	0.23 ± 0.01^{ab}	0.23 ± 0.04^{ab}	0.19 ± 0.02^{a}	0.19 ± 0.01^{a}	0.22 ± 0.00^{ab}
C17:0	1.15 ± 0.09	1.06 ± 0.13	1.46 ± 0.11	1.35 ± 0.00	1.17 ± 0.00	1.27 ± 0.00	1.80 ± 0.79	1.42 ± 0.00
C18:0	31.87 ± 1.72^{ab}	27.78 ± 1.73^{a}	33.67 ± 2.27^{b}	35.25 ± 0.45^{b}	35.09 ± 2.87^{b}	34.11 ± 0.53^{b}	34.13 ± 0.97^{b}	35.37 ± 0.05^{b}
C18:1	34.22 ± 1.51^{a}	40.45 ± 1.22^{b}	33.56 ± 0.83^{a}	33.50 ± 0.87^{a}	33.78 ± 0.01^{a}	35.99 ± 0.32^{a}	35.08 ± 0.23^{a}	32.48 ± 0.43^{a}
C18:2	3.01 ± 0.14^{bc}	2.77 ± 0.09^{b}	2.93 ± 0.11^{bc}	3.81 ± 0.18^{d}	2.69 ± 0.41^{b}	2.12 ± 0.06^{a}	2.12 ± 0.05^{a}	3.19 ± 0.01^{c}
C18:3	0.33 ± 0.02^{ab}	0.33 ± 0.02^{ab}	0.37 ± 0.04^{b}	0.33 ± 0.01^{ab}	0.31 ± 0.06^{ab}	0.25 ± 0.00^{a}	0.33 ± 0.06^{ab}	0.36 ± 0.01^{b}
C20:0	1.32 ± 0.03^{b}	1.17 ± 0.03^{a}	1.39 ± 0.08^{bc}	1.08 ± 0.01^{a}	1.32 ± 0.12^{b}	1.31 ± 0.01^{b}	1.50 ± 0.02^{cd}	1.58 ± 0.01^{d}
C20:1	0.04 ± 0.00^{b}	0.06 ± 0.00^{cd}	0.04 ± 0.00^{b}	0.06 ± 0.00^{bc}	0.05 ± 0.01^{bc}	0.07 ± 0.01^{d}	0.05 ± 0.00^{bc}	0.00 ± 0.00^{a}
C22:0	0.22 ± 0.00^{abc}	0.20 ± 0.01^{ab}	0.24 ± 0.02^{bc}	0.18 ± 0.00^{a}	0.22 ± 0.02^{ab}	0.22 ± 0.00^{ab}	0.26 ± 0.01^{cd}	0.29 ± 0.00^{d}
ΣSFA	62.12 ± 1.68^{b}	56.14 ± 1.31^{a}	62.86 ± 0.87^{b}	62.07 ± 0.65^{b}	62.94 ± 0.93^{b}	61.38 ± 0.86^{b}	62.23 ± 0.35^{b}	63.75 ± 0.45^{b}
ΣUFA	37.88 ± 1.68^{a}	43.86 ± 1.31^{b}	37.14 ± 0.87^{a}	37.93 ± 0.65^{a}	37.06 ± 0.93^{a}	38.62 ± 0.86^{a}	37.77 ± 0.35^{a}	36.25 ± 0.45^{a}
ΣMUFA	34.54 ± 1.52^{ab}	40.76 ± 1.19^{c}	33.83 ± 0.81^{ab}	33.79 ± 0.48^{ab}	34.06 ± 0.96^{ab}	36.26 ± 0.77^{b}	35.32 ± 0.24^{ab}	32.70 ± 0.43^{a}
ΣPUFA	3.35 ± 0.16^{bc}	3.10 ± 0.11^{b}	3.30 ± 0.06^{bc}	4.14 ± 0.18^{d}	3.00 ± 0.02^{b}	2.36 ± 0.09^{a}	2.45 ± 0.11^{a}	3.55 ± 0.02^{c}

Note: Values expressed as means ± standard deviation of the replications. Numbers in the same row and followed by the same letter show no significant difference based on Tukey HSD test at 5% of significance. C14:0= myristic, C15:0= pentadecanoic, C16:0= palmitic, C16:1= palmitoleic, C17:0= margaric, C18:0= stearic, C18:1= oleic, C18:2= linoleic, C18:3= linolenic, C20:0= arachidic, C20:1= gadoleic, C22:0= behenic acids. ΣSFA= sum of saturated FA, ΣUFA= sum of unsaturated FA, ΣMUFA= sum of mono-unsaturated FA, ΣPUFA= sum of poly-unsaturated FA. SG= Sigi, BG= Banggai, TL= Toli-toli, BU= Buol, PO= Poso, PM= Parigi Moutong, MU= Morowali Utara, and DG= Donggala

Cocoa butter from SG contains the highest levels of palmitic and palmitoleic acids, but the lowest levels of stearic acid. Conversely, cocoa butter from PO contains the highest levels of stearic and linoleic acids, but the lowest levels of palmitic acid. According to Mustiga *et al.* (2019), palmitic acid content is negatively correlated with stearic, oleic, and linoleic acid content. This is in line with palmitic acid's role as a precursor for the formation of stearic acid and other long-chain fatty acids in plant lipid biosynthesis (AID, 2020). Meanwhile, cocoa butter from BG exhibits different characteristics, containing the highest levels of oleic acid (40.45%), but the lowest levels of stearic acid (27.78%) and arachidic acid (1.17%). This aligned with previous measurements of FFA levels as oleic acid (Table 1). Conversely, the highest stearic acid content was obtained from BU cocoa butter (35.37%), but the lowest oleic acid (32.5%). The observed trend is that if oleic acid is high, stearic acid content is low, and vice versa, in accordance with results reported by Hatmi *et al.* (2021) and Chaiseri and Dimick (1989).

Ribeiro *et al.* (2012) reported that minor variation in FA, particularly linoleic acid, reflect the geographical origin of cocoa butter. The author also states that South America cocoa butter linoleic acid level was higher (>3%) compared to those from Africa (2.5–3%) and Asia (<2.5%). However, contrary to what expected, results showed inconsistent level of linoleic acid. Only DG and PM presented linoleic acid lower than 2.5%. BG, TL and MU presented linoleic acid in between 2.5 to 3%. SG, PO and BU presented linoleic acid higher than 3%. Therefore, we assumed that grouping cocoa butter characteristics by country is too broad to be used as a reference. Moreover, compared to Brazilian cocoa butter (linoleic acid levels of 2.5–3%) (Vieira *et al.*, 2015), Central Sulawesi samples varied more widely (2.1–4.1%) which suggests that regional microclimates and post-harvest technique within a single province can produce variability comparable to differences between continents.

Significant regional differences were observed in the sum of saturated (SFA), unsaturated (UFA), monounsaturated (MUFA), and polyunsaturated (PUFA) fatty acids in cocoa butter (Table 2). Previous studies have established that cocoa grown in areas with high temperatures has higher SFA content (Vieira *et al.,* 2015; Firmanto *et al.,* 2019). The maximum temperature in cacao plantation areas in Central Sulawesi is relatively high, ranging from 29 to 34 °C. Consistently, the proportion of SFA (56.14–63.75%) from Central Sulawesi, were higher than UFA (36.25–43.86%). Cocoa butter from BU contains the highest amount of SFA and the lowest levels of UFA and MUFA. Conversely, BG cocoa butter results the highest amount of UFA (43.86%) and MUFA (40.76%), but the lowest amount of SFA. This BG butter show distinct FA profile which has not been previously reported by Firmanto *et al*. (2019) for Indonesian cocoa butter. Meanwhile, PUFA was the highest in PO cocoa butter, but lowest in DG cocoa butter.

Triacylglycerol profile

The triacylglycerol (TAG) composition of cocoa butter from Central Sulawesi is shown in Table 3. A total of 9 different TAGs were identified. The TAG compounds and the amount of SUS, SUU, and SSS were significantly different (p<0.05) between each district. On the contrary, minor TAG such as SOA did not differ significantly between districts. The major TAGs identified were POP (14.87–18.77%), POS (40.91–43.23%), and SOS (27.6–31.42%). The variation of these major TAGs was relatively small compared to differences in specific TAGs between origins reported by Sirbu *et al*. (2018), which extended up to 2.5-fold. POP content was lower than POS and SOS content in all samples, which align with previous studies indicating that cocoa butter from Malaysia and Indonesia contains low levels of POP and high levels of SOS (Hernandez *et al.,* 1991).

Table 3. Triacylglycerol composition of cocoa butter from eight districts in Central Sulawesi

TAG (%)	Districts							
	SG	BG	TL	PO	MU	DG	PM	BU
OOO	1.76 ± 0.14^{bc}	1.26 ± 0.17^{ab}	1.48 ± 0.05^{abc}	1.92 ± 0.03^{c}	1.14 ± 0.13^{a}	1.33 ± 0.11^{ab}	1.23 ± 0.13^{ab}	1.32 ± 0.28^{ab}
POO	1.78 ± 0.33^{a}	2.72 ± 0.08^{b}	1.66 ± 0.05^{a}	2.15 ± 0.04^{ab}	3.70 ± 0.29^{c}	3.72 ± 0.25^{c}	2.15 ± 0.12^{ab}	1.53 ± 0.13^{a}
PLS	2.41 ± 0.11^{b}	0.94 ± 1.32^{ab}	2.47 ± 0.00^{b}	2.76 ± 0.01^{b}	1.68 ± 0.44^{ab}	0.13 ± 0.18^{a}	1.58 ± 0.02^{ab}	2.63 ± 0.05^{b}
POP	18.55 ± 0.04^{c}	16.75 ± 0.85^{abc}	18.28 ± 0.70^{bc}	14.87 ± 0.01^{a}	16.54 ± 0.56^{a}	17.37 ± 0.44^{bc}	$17.68\pm0.29b^{c}$	18.20 ± 0.26^{bc}
SOO	2.35 ± 0.02^{a}	3.99 ± 0.13^{c}	2.20 ± 0.02^{a}	3.90 ± 0.03^{bc}	3.93 ± 0.26^{bc}	5.78 ± 0.26^{d}	3.30 ± 0.24^{b}	2.22 ± 0.07^{a}
POS	42.78 ± 0.54^{cd}	41.93 ± 0.12^{abc}	42.28 ± 0.22^{bc}	40.91 ± 0.17^{a}	42.14 ± 0.09^{bc}	41.60 ± 0.25^{ab}	42.81 ± 0.05^{cd}	43.37 ± 0.32^{d}
PPS	0.90 ± 0.11^{b}	0.00 ± 0.00^{a}	0.78 ± 0.08^{b}	0.85 ± 0.01^{b}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.75 ± 0.18^{b}	0.93 ± 0.08^{b}
SOS	27.28 ± 0.24^{a}	29.44 ± 0.15^{d}	28.06 ± 0.20^{bc}	31.42 ± 0.07^{e}	28.58 ± 0.34^{c}	28.61 ± 0.17^{c}	28.60 ± 0.13^{c}	27.53 ± 0.13^{ab}
SOA	1.03±0.03	0.00±0.00	1.40±0.47	1.21±0.01	1.13±0.14	0.00±0.00	0.95±0.24	0.99±0.20
ΣSUS	92.05 ± 0.66^{de}	89.05 ± 0.74^{ab}	92.50 ± 0.24^{de}	91.18 ± 0.09^{cd}	90.06 ± 0.02^{bc}	87.70 ± 0.15^{a}	91.61 ± 0.15^{de}	92.70 ± 0.08^{e}
ΣSUU	4.12 ± 0.31^{a}	6.71 ± 0.20^{cd}	3.86 ± 0.07^{a}	6.05 ± 0.07^{bc}	7.63 ± 0.55^{d}	9.50 ± 0.00^{e}	5.45 ± 0.12^{b}	3.75 ± 0.20^{a}
ΣSSS	0.90 ± 0.11^{b}	0.00 ± 0.00^{a}	0.78 ± 0.08^{b}	0.85 ± 0.01^{b}	0.00 ± 0.00^{a}	0.00 ± 0.00^{a}	0.75 ± 0.18^{b}	0.93 ± 0.08^{b}

Note: Values expressed as means ± standard deviation of the replications. Numbers in the same row and followed by the same letter show no significant difference based on Tukey HSD test at 5% of significance. P= palmitic, S= stearic, O= oleic, L= linoleic, and A= arachidic acids. SSS= trisaturated, SUS= disaturated-monounsaturated, and SUU= monounsaturated-diunsaturated triacylglycerol. SG= Sigi, BG= Banggai, TL= Toli-toli, BU= Buol, PO= Poso, PM= Parigi Moutong, MU= Morowali Utara, and DG= Donggala

The present results confirmed a higher POS content compared to SOS and POP in all samples studied. This pattern aligns with the typical cocoa butter composition previously studied (Chaiseri and Dimick, 1989; Vieira *et al.,* 2015; Figueira and Luccas, 2022). The high oleic acid composition in the BG sample contributes to its elevated SUU group composition. The presence of dominant unsaturated fatty acids can influence TAG formation (Yao *et al.,* 2020). Moreover, cocoa cultivated at higher altitudes, such as PO (>700 m a.s.l.) exhibited the highest SOS content, in line with Sirbu *et al.* (2018).

The approach of grouping TAGs based on their degree of unsaturation (e.g., SSS, SUU, and SUS) was used to simplify the interpretation of a fat physical properties (Ribeiro *et al.,* 2012). As shown in Table 3, the total contents of SUS, SUU, and UUU ranged between 90.72–93.83, 3.90–7.50, and 0.48–0.95%, respectively. The proportion of symmetrical monounsaturated TAG such as SUS is directly associated with the hardness properties of cocoa butter, due to its unique crystal structure arrangement (Buscato *et al.,* 2017). Overall, the results showed a high proportion of SUS in cocoa butter from all districts. Even the lowest proportion of SUS (87.7%, DG butter) was still higher than the proportion of SUS in Indonesian commercial cocoa butter (85.1%) reported by Tandean (2009). On the other hand, elevated levels of POO and SOO indicate a softer cocoa butter profile (Chaiseri and Dimick, 1989). In the present study, the total sum of POO and SOO were reported collectively as the SUU group. Cocoa butter from BG, MU and DG exhibited high levels of SUU, with no detectable levels of SSS-type TAGs. This confirms that even within Indonesia, significant differences exist between districts, therefore it's important to determine of origin characterization.

Slip melting point

Slip melting point (SMP) is a standard metric used to evaluate the physical properties of fats and oils, particularly their hardness, solidification, and melting characteristics. For cocoa butter, SMP corresponds to the onset of melting where 4% fraction of the fat remains solid while the majority has melted (Buscato *et al.,* 2017; Figueira and Luccas, 2022). The results of cocoa butter SMP presented in Table 4, ranged from 29.5 to 32.22 °C and were significantly different between districts. Cocoa butter from BG and DG recorded the lowest SMP (<30 °C), slightly lower than the SMP of Indonesian commercial cocoa butter (31.8–32.6 °C), reported by Tandean (2009). Conversely, cocoa butter from BU, SG, and TL exhibited higher SMP (>31 °C). The SMP of cocoa butter from MU and PO fell within the intermediate range of 30–31 °C.

The SMP of cocoa butter depends not only on its TAG composition but also on its complex crystallization behavior. Cocoa butter is polymorphic, meaning it can form six different crystal structures (polymorphs I-VI, α, β', and β), each with a different melting point and stability (Ghazani and Marangoni, 2021). The most stable crystal structure is βV, with a melting point ranging from 29 to 34 °C. To achieve this stable structure, cocoa butter must undergo a crystal bond rearrangement process called tempering (Indarti *et al.,* 2013). Since this study used raw (un-tempered) cocoa butter, slightly lower SMP was expected. However, we observed a trend that the higher SFA content and SUS proportions, which favor the more formation of stable β polymorphic crystals, the higher SMP discovered in samples (BU, TL, and SG). In contrast, higher proportions of SUU could disrupt crystal packing, resulting in lower melting temperatures. These findings confirm that the composition of fatty acids and TAGs significantly influence the SMP of cocoa butter.

Solid fat content

The melting behavior of fats and oils is quantitatively expressed through the solid fat content (SFC). SFC reflects the proportion of fat that remains solid at specific temperatures, influencing the texture, mouthfeel, and stability of food products. Figure 4 displayed the SFC curves of cocoa butter from eight districts in Central Sulawesi. It showed that SFC curve was similar in shape, but there are differences in the slope of the curves at between temperatures of 10–20, 20–25, and 25–30 °C. Moreover, SFC at 30 °C was less than 3% and then melts completely at 35 °C. SFC profile of cocoa butter from Central Sulawesi is consistent with the typical SFC profile of cocoa butter that has been studied previously (Norazlina *et al.,* 2023). Ideally, SFC of cocoa butter should be higher than 50% at 25 °C, then rapid reduction of SFC occurs at 27–33 °C and then no SFC above 35 °C to avoid the formation of residues such as a waxy layer (Ribeiro *et al.,* 2012).

Tabel 4. Slip melting point (SMP) cocoa butter from eight districts in Central Sulawesi

Sample	SG	BG	TL	PO	MU	DG	PM	BU
SMP (°C)	31.45± 0.31[bcd]	29.50± 0.24[a]	31.65± 0.17[cd]	30.22± 0.16[ab]	30.50± 0.52[abc]	29.79± 0.02[a]	30.00± 0.61[a]	32.22± 0.30[d]

Note: Values expressed as means ± standard deviation of the replications. Numbers in the same row and followed by the same letter show no significant difference based on Tukey HSD test at 5% of significance. SG= Sigi, BG= Banggai, TL= Toli-toli, BU= Buol, PO= Poso, PM= Parigi Moutong, MU= Morowali Utara, and DG= Donggala

The SFC of cocoa butter from Central Sulawesi at temperatures of 15, 20, 25, and 30 °C is differed significantly between regions. Cocoa butter from BU, TL, SG, and PO showed the highest SFC percentage at 20 °C, in line with the results of SMP, the high amount of SFA, and the total TAG, SUS, and SSS. The SFC results at 25 °C (15.6–36.9%) were lower compared to the SFC of cocoa butter from previous studies, which were 60–70% (Vieira *et al*., 2015; Piravivanak *et al.,* 2023). In addition, we found that cocoa butter from other districts had similar SFC profile reported by Solís-Fuentes and Durán-de-Bazúa (2004), excluding cocoa butter from BG.

The absence of tempering process, which converts fat crystals into the ideal βV crystals, could contribute to the lower SFC at 25 °C compared to previous reports. Without a controlled pre-crystallization in tempering process, the fat crystallizes in a mixture of less stable polymorphs which melt more easily. Furthermore, the sample used was unrefined cocoa butter which still contains minor components such as DAGs, MAGs, FFAs, phospholipids, sterols, and other components. It is known to delay or inhibit ideal crystallization and further reduce the solid fraction at intermediate temperatures (Chen *et al.,* 2021).

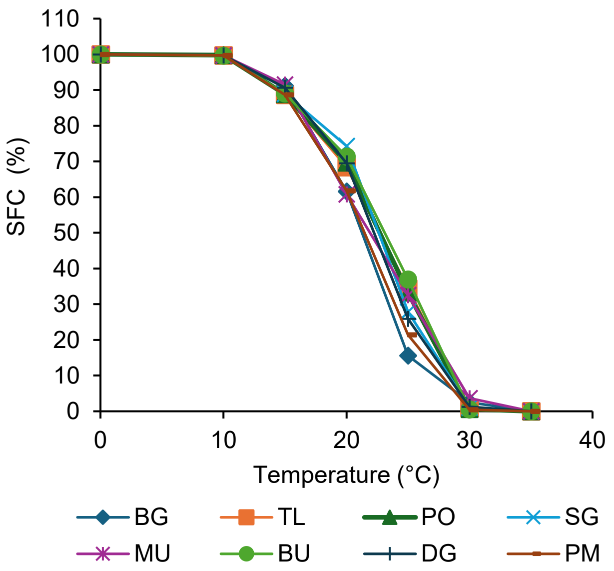

Figure 4. Solid fat content (SFC) of cocoa butter from eight districts in Central Sulawesi as a function of temperature. SG= Sigi, BG= Banggai, TL= Toli-toli, BU= Buol, PO= Poso, PM= Parigi Moutong, MU= Morowali Utara, and DG= Donggala

In addition, we observed that cocoa butter from BG which record high FFA, unsaturated FA, and low SMP temperature, also had exhibited the sharpest SFC decline and the lowest SFC at 25 °C, confirming its low thermal stability. Soft cocoa butter typically requires additional treatments such as fractionation and blending with harder fats to produce a stable product in solid form at room temperature (Norazlina *et al.,* 2023). Soft BG butter unsuitable for chocolate manufacture but potentially useful as a blending component for other industries.

Sample clustering based on physicochemical profiles

In order to understand the relationships between various chemical and physical characteristics of cocoa butter, a correlation analysis was performed. The results of the correlation analysis were presented in Figure 5. Correlation analysis revealed a strong positive relationship among FFA, UFA, and MUFA (r>0.8). Conversely, these variables were negatively correlated (r>-0.8) with SFA, SFC 25 °C, and SMP. Meanwhile, SFC 20 °C and SFC 25 °C showed a positive correlation with SUS and SSS, but negatively correlated with SUU. Therefore, it can be predicted that if the FFA of the sample is high, cocoa butter will tend to have higher UFA, MUFA, and SUU, but lower SUS, SMP, and SFC.

PCA was performed on auto-scaled variables (mean= 0, SD= 1) using the correlation matrix to ensure equal weighting of compositional and physical parameters with different units. As shown in Figure 6, the PCA revealed that two principal components explained 79.2% of the total variability, with PC1 contributing 61.0% and PC2 contributing 18.2%. PC1 clearly separates samples along a hardness or melting stability axis, with higher SFA, SUS, SMP, and SFC 20–25 °C on the positive side, and higher UFA, MUFA, FFA, and SUU on the negative side. PC2 discriminates based on minor TAG, PUFA, and SFC at 30 °C, indicating the solid content near body temperature. This is consistent with the known relationship between the degree of triacylglycerol unsaturation and thermal stability.

Variables such as SFA, SFC 20 °C, SFC 25 °C, SUS, SSS, and SMP on the positive side of PC1 indicated that these characteristics were predominantly found in the sample groups located on the right side of the biplot (BU, TL, SG, PO). Conversely, variables such as UFA, MUFA, FFA, and SUU (negative side of PC1), were dominant in BG samples located on the left. On the positive side of PC2, the DG and MU sample groups showed dominant SUU and SFC 30 °C variables. PM samples appeared more centralized, indicating a more balanced chemical and physical profile.

Sample clustering in the PCA biplot based on the main variables such as FFA, total of SFA and UFA, triglyceride groups (SUS, SUU, SSS) and physical properties (SFC, SMP) confirms the variation of cocoa butter between regions. To our knowledge, this is the first study to use PCA to reveal four distinct geographic clusters of cocoa butter within a single

Indonesian province. Our PCA approach integrates chemical (FFA, SFA, MUFA, TAG distribution) and physical (SMP, SFC) properties. Therefore, these findings could become a reference for manufacturers to anticipate functional performance based on origin. Industry could apply sourcing strategies such as clustering districts with hard butter and thermal stability for direct chocolate manufacture, while allocating soft butter origins for blending or alternative applications (Beckett *et al.,* 2017).

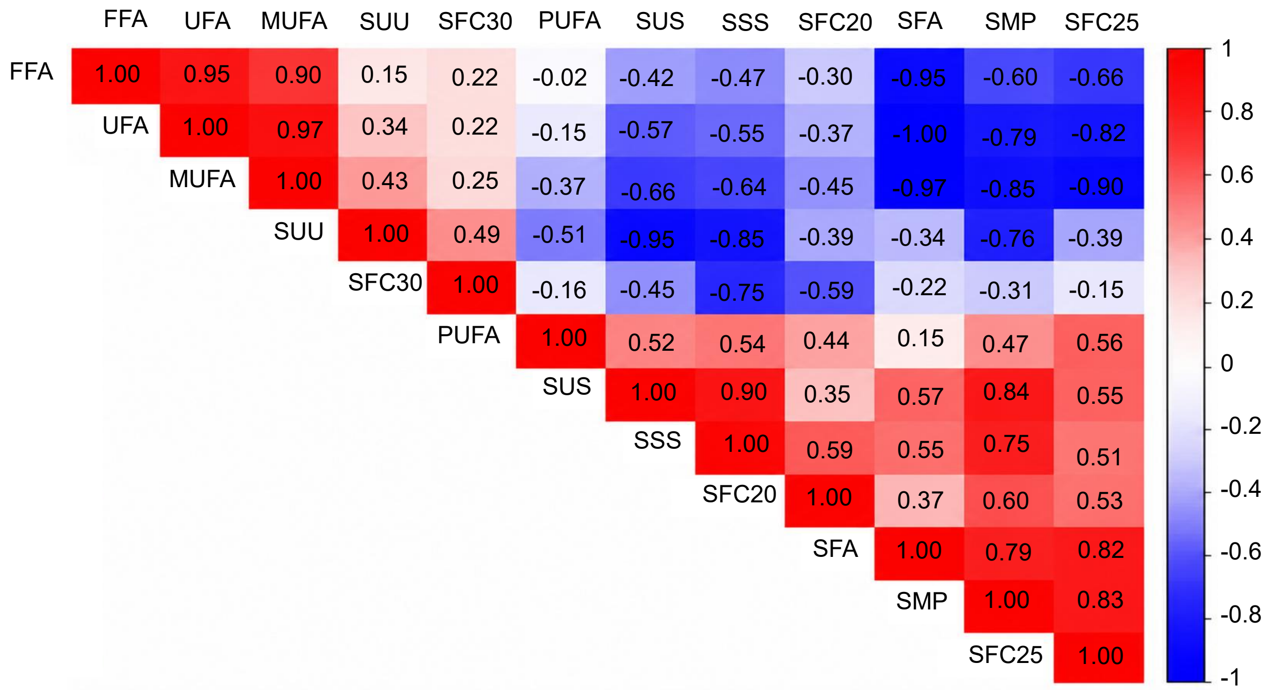

Figure 5. Correlation matrix of cocoa butter characteristics between variables such as FFA, UFA, MUFA, SFA, SUS, SUU, SSS, SMP, and SFC at 20 °C, 25 °C, and 30 °C based on Pearson correlation coefficient, r, ranging from +1 to -1. Correlation is significant at the 0.05 level. FFA= free fatty acids, UFA= unsaturated, MUFA= mono-unsaturated FA, SFA= saturated FA, PUFA= poly-unsaturated FA, SUS= disaturated-monounsaturated, SUU= monounsaturated-diunsaturated triacylglycerol, SSS= trisaturated, SMP= slip melting point, SFC20= solid fat content 20 °C, SFC25= solid fat content 25 °C, SFC30= solid fat content 30 °C

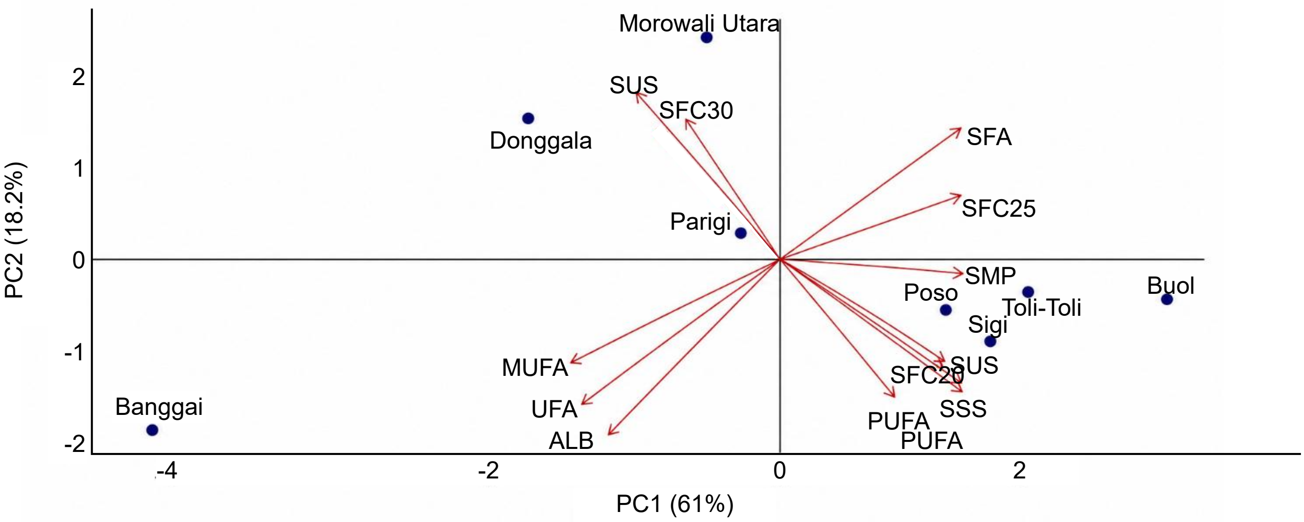

Figure 6. Principal component analysis (PCA) biplot showing clustering of cocoa butter from eight districts. Samples group into four distinct cluster: 1= Banggai, 2= Donggala and Morowali Utara, 3= Parigi, 4= Poso, Toli-toli, Sigi, and Buol. ● = sampling location

CONCLUSION

This study demonstrates that geographic origin significantly influences the physicochemical properties of cocoa butter within Central Sulawesi, with clear regional differences in moisture, free fatty acids, fatty acid and triacylglycerol composition, slip melting point, and solid fat content. Cocoa butter from BU, SG, TL, MU, PM, and PO met the industrial and CODEX quality requirements, but substandard cocoa butter from BG reinforce the need for improved post-harvest practice and quality control. Correlation analysis revealed consistent relationships between chemical composition and physical properties, while PCA identified four distinct geographic clusters of cocoa butter. Harder cocoa butter clusters (high SUS and SFA) may be prioritized for direct chocolate manufacturing, whereas softer butter may be optimized through blending or fractionation. This approach provides a more comprehensive understanding by linking fatty acid and TAG composition to functional melting behavior. These findings can support the development of technological strategies to optimize the utilization of cocoa butter as a raw material. Overall, the results of this study provide both scientific evidence and practical guidance for developing Central Sulawesi as a competitive source cocoa butter in the global market.

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