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QUALITY CHARACTERISTICS AND THERMAL BEHAVIOR DIVERSITY OF TRADITIONAL CRUDE SHEA (*VITELLARIA PARADOXA GAERTN*) BUTTER FROM BURKINA FASO

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KEYWORDS : Shea butter ; Extraction process ; Solid fat content ; Differential scanning calorimetry ; Chemical quality ; Burkina Faso

ABSTRACT

The aim of this study was to establish a comparative analysis of the physicochemical and the thermal behavior by *p-NMR* for solid fat content (SFC), and differential scanning calorimetry (DSC) of shea butter (SB) from Burkina Faso, related to different traditional extraction processes. Thirty-seven samples obtained from different localities were collected from local producers and analyzed for chemical indexes, unsaponifiable matter content (UMC), color, yellow index, fatty acids (FA) profile, and thermal behavior. Results showed that stearic acid (34%—47.2%) and oleic acid (40.8%—51%) were the most abundant FA. Chemical quality variations among those samples were observed: UMC (3.0%±1.0%—12.0%±0.1%), peroxide value (4.6 ± 0.1 to 44.5 ± 0.2 meqO_2/kg), iodine value by GC (50.5 to 64.2), free fatty acids (1.1%±0.1%—9.7%±0.1%). Statistically significant relationships were observed between thermal properties and chemical parameters. The results were subjected to clustering and principal component analysis (PCA). Results showed that a great diversity exists among crude shea butter samples from Burkina Faso which is due to both regional variation and difference in extraction processes. A standardization of the process could help to improve the quality.

ABBREVIATIONS AND ACRONYMS

AV : Acid value | CA : Clusters analysis | CBE : Cocoa butter equivalent | C18 : 0:Stearic fatty acid | C18 : 1:Oleic fatty acid | DAG : Diacylglycerols | DSC : Differential scanning calorimetry | FA : Fatty acid | FAME : Fatty acids methyl ester | FFA : Free fatty acid | GC : Gas chromatography | Hf : Enthalpy of fusion | IV : Iodine value | K : Specific extinction | PC : Principal components | PV : Peroxide value | p-NMR : Pulsed nuclear magnetic resonance | SB : Shea butter | SFC : Solid fat content | TAG: Triacylglycerols | UMC : Unsaponifiable matter content | UV: Ultraviolet | YI : Yellow index | ΔK: Variation of the specific extinction | ΔH : Enthalpy ratio

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Introduction

Shea (*Vitellaria paradoxa C.F. Gaertn*) is a tree that grows naturally throughout Sahelo-Sahelian band particularly in areas called "shea belt" that include Burkina Faso, unlike the *V. paradoxa nilotica* subspecies which is present in East Africa [1]. The shea belt consists of sixteen African countries, the main producers are Nigeria, Mali, Burkina Faso and Ghana. The shea area covers 70% of the Burkina Faso territory [2], among wich 37 of the 45 provinces. The following provinces represented the high shea nuts potential, namely Houet (West), Ioba (South-West), Nahouri (SouthCentral), Kadiogo (Central), and Sissili (Mid-West), [3].

Shea kernels are used to extract shea butter (SB). The extraction of SB in Africa, is not standardized yet, and it is usually done manually or semi-mechanized [4]. SB extraction is done from shea nut collected mostly by African women according to Nahm et al. [1], who described three methods: West African boiling, West African oven, and East African raw methods. Three major traditional butter processing have been described by Saussey [5]: cooking, churning, and the "quality" technique; the latter differs from the others by kernels washing and sorting before processing, double cooking, and crude butter filtering. The qualitative and quantitative composition of SB are related to its origin, the genetic variation, the climatic factors and well as the seasonal variations and extraction processing [1, 6-8]. Pretreatments factors, such as kernel crushing, nuts, kernels heating temperature and duration are factors with having great impact on butter quality [9-11].

Shea butter has been traditionally used in Africa for many centuries as a source of green energy, in food, body care as well in traditional pharmacopoeia [5]. Nowadays, in food sector, SB is used to produce cocoa butter equivalents (CBEs) [6]. CBEs are vegetable fats with physicochemical properties similar to those of cocoa butter (CB) and have been used in confectionary products for several years. For the cosmetic industry the great interest of SB is due to its particular high unsaponifiable matter content (UMC), which consists of triterpenic alcohols, kariten, sterol, tocopherol, phenols, etc., and its ability to absorb UV-A and UV-B radiation [12-16]. Another interesting property is the antioxidant activity due mostly to phenolic compounds and tocopherols mainly in the unsaponifiable fraction [1, 17, 18].

According to Iddrisu et al. [19], chemical parameters such as moisture content, free fatty acids (FFA), peroxide value (PV) and insoluble impurities are important quality indicators for unrefined SB. The presence of moisture in fats activates lipases, stimulates the growth of microorganisms and leads to the hydrolysis of triglycerides. According to the Codex Alimentarius [20] the specifications of these quality parameter allowed to distinguish two categories of butter: butter for direct consumption (grade 1[a]) and butter for food industries (grade 1[b]) as described in Table 1.

The traditional technique is the main method used in Burkina Faso for the extraction of SB. However, this method is labor-intensive, time-consuming and requires large quantities of water and firewood. Moreover, the quality of the SB produced can be affected, particularly due to the specific treatment and extraction processes. Burkina Faso use a regional standard (NBF 01-005 : 2006) [21] for the quality criteria of crude SB, which is similar to the Codex Alimentarius standards. This standard also defines a third category intended for soap factories. It can also be consumed after refining. The

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processing of crude SB into agri-food products in Burkina Faso is still in its early stages. Rich in vitamins and minerals, SB is used as a cooking oil in various dishes in Burkina Faso. Since 2003, more Trans-National Corporations producing CBEs have been involved in sourcing shea kernels to meet the growing demand for food products and cosmetics [22]. In line with this trend, a factory for mechanized SB production has been implemented in Bobo-Dioulasso (Burkina Faso), with its refining unit located in St-Léonard (France) [23]. Some small chocolate production units also have recently been developed in Ouagadougou, but they remain very limited. In Burkina Faso, SB producers are federated in an association called "*table filière karité*" to produce SB for used as an edible product, in cosmetics, soaps, traditional medicines, and for cultural purposes [24]. Most SB produced in the country is exported and processed in Europe. According to Seghieri [25], Burkina Faso stands as the main supplier of SB to some cosmetics firms around the world. In 2021, the Ministry of Industry, Trade and Crafts labeled crude SB produced in Burkina Faso "*Beurre de karité du Burkina Faso*" as part of a vision to enhance and promote local products.

Shea butter, like other vegetable fats, is mainly composed of triacylglycerols (TAG) ranging from 77.7 to 92.4%, with the presence of diacylglycerols (DAG) varying from 7.6 to 22.6% [26]. According to Davrieux et al. [27], the fatty acid (FA) profiles of West African and East African butter are different, with stearic acid (C18:0) content of about 41% and 30%, respectively. The high stearic acid content is one of the factors responsible for shea butter's hard consistency, while the oleic acid (C18:1) contributes to its semi-solid consistency [9, 28]. Unsaponifiable matter corresponds to a minor fraction of SB but is found in higher levels (4—11%) compared to other fats (0—2%) [1]. According to a study carried out in Northern Ghana, the UMC of unrefined butter is not correlated with the extraction process, but rather with environmental conditions and the genetic material of shea trees [29]. In contrast, Megnanou et al. [30] showed that the UMC of SB obtained from optimized extraction conditions was significantly higher (17.6%) than that from local market (1.7%), which was obtained by the common traditional method.

The organoleptic characteristics of crude SB from Ivory Coast, such as odor, color and consistency, have been widely reported by Megnanou et al. [30]. Yellow butter was the most common color, accounting for 67.90% of all samples, while beige butter represented about 29.5% and grey butter about 2.5%. Differential scanning calorimetry (DSC) thermograms and solid fat content (SFC) by *p-NMR*, are physical methods providing data of fats and oils regarding their properties, which are important for their functionality and application [31].

The aim of this study was to establish the diversity, and the relationship between the physicochemical and the thermal behaviour/ properties of shea butter obtained by different traditional extraction processes from different localities from Burkina Faso.

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***Table 1**. Quality criteria of unrefined shea butter according to Codex Alimentarius*

Characteristics	Unrefined shea butter		
	Grade 1[a]	Grade 1[b]	
	Maximum level	Minimum level	Maximum level
Water content (%)	0.05	0.06	0.2
Free fatty acids (%)	1	1.1	3
Peroxide value ($mEqO_2/kg$)	10	11	15
Insoluble impurities (% m/m)	0.09	0.1	0.2

Materials and methods

BIOLOGICAL MATERIAL AND CHEMICALS

BIOLOGICAL MATERIAL AND DATA COLLECTION

Burkina Faso has 13 different regions, and only one (Sahel) does not produce SB. The production potential varies considerably between regions. Thirty-seven samples of fresh crude SB (around 1 kg of butter per producer) were collected directly from local producers in various areas of Burkina Faso, along with the relevant information on the production processes. The Figure 1 presents the provinces of the collection area (highlighted in green). The areas where the material are collected were chosen based on available database of the organization "*table filière karité*" [24], selecting localities with important shea sectors. The ratio per province was at least two samples per producer. The study used a participatory approach involving local producers on-site, with limitations such as refusals noted in some participants. Individual survey forms were filled out with producers to collect data regarding all steps in the SB production chain, similar to method described by Zida et al. [32]. We collected the samples from the producing localities and transported them to the laboratory in Ouagadougou using a cool box. Then, the samples were melted and placed in amber glass flasks, which were stored at 4 °C. Subsequently, they were transferred to Belgium under refrigerated conditions and maintained under that storage temperature and in the dark until further analyses.

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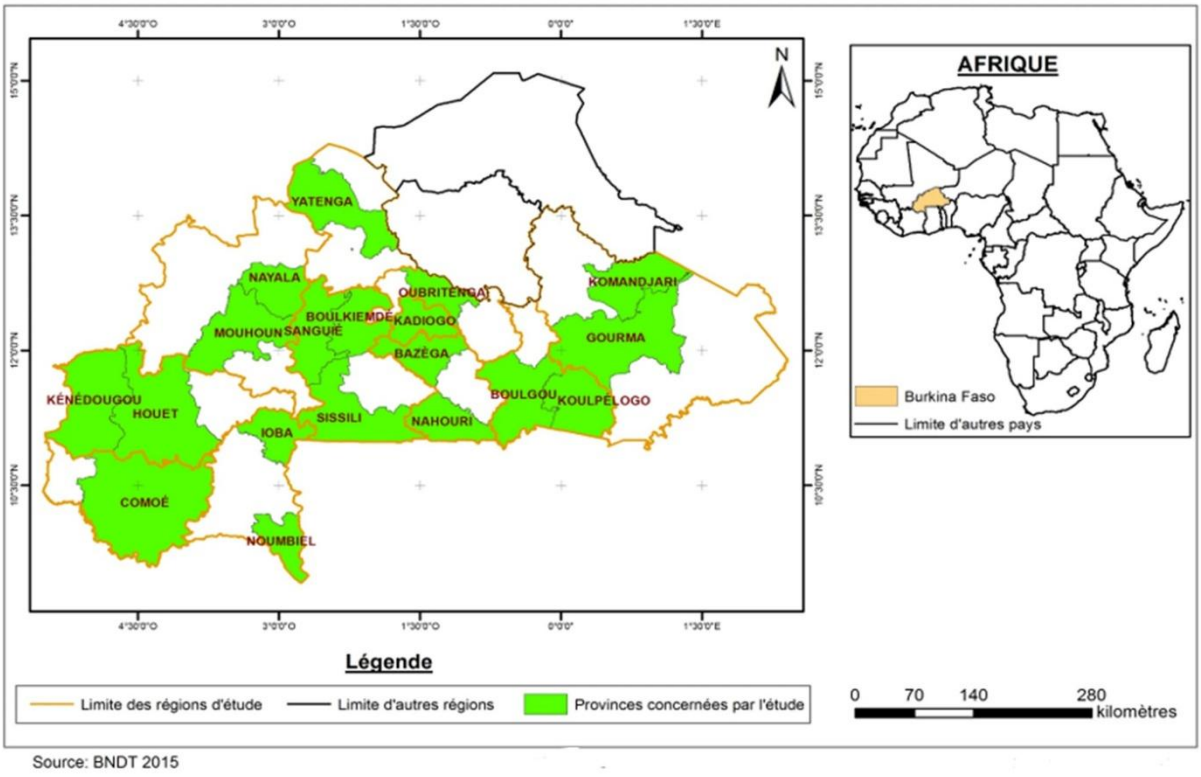
***Figure 1**. Mapping of the shea butter collection. (Source: BNDT 2015 ("Institut Géographique du Burkina Faso"))*



CHEMICALS

Analytical grade solvents, standards and reagents were used to perform the analyses. Isooctane and petroleum ether were from Carlo Erba (Paris, France); ethyl alcohol 95%, diethyl ether, potassium hydroxide, acetic acid, sodium hydroxide and sodium dodecyl sulfate, were purchased from VWR Prolabo Chemicals (Leuven, Belgium). Sodium thiosulfate, sodium chloride, n-heptane and standards such as Wijs solution were provided from Merck (Darmstadt, Germany). Boron trifluoride-methanol solution (BF3-MeOH 14%) was provided by Sigma-Aldrich, Switzerland.

Methods

CHEMICAL ANALYSIS

DETERMINATION OF CHEMICAL INDEXES

The official methods and recommended practices of the AOCS [33] were applied to determine the iodine value (IV) by Wijs: AOCS Tg 1a-64; and IV by GC from FA composition: (AOCS Cd 1c-85), and PV (Cd 8b-90 2009). The unsaponifiable matter content (AOCS Ca 6b 53), the specific extinction (Kλ at

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232 nm and 268 nm; AOCS Ch 5-91) and the variation of the specific extinction (ΔK) were performed according to AOCS [33]. Specific extinction and the ΔK were determined using an Agilent 8453 UV-Vis spectrophotometer (Victoria, USA). The acid value (AV) was determined according IUPAC [34] and the FFA was calculated as oleic acid according to (AOCS Ca 5a-40).

SHEA BUTTER FATTY ACIDS PROFILE DETERMINATION

Gas chromatography (Agilent 6890 GC, USA), equipped with flame ionization detector (GC-FID, USA) was used to determine the FA profile. Firstly, fatty acids methyl ester (FAME; AOCS Ce2-66) was prepared following AOCS [33]. Shea butter (100—250 mg) was diluted in 4mL of NaOH 0.5 M. Then, 5mL of BF3-MeOH 14% was added through the condenser, before adding 4mL of n-heptane in mixture and boil along 1 min. Afterwards, 20mL of saturated NaCl was added, and then shaken vigorously for 30 s. Then, 1mL of the top layer solution (FAME), was collected mix to n-heptane at a final concentration 1/10, according to the optimized protocol of AOCS Ce 1—62. The GC analytical conditions were as follow:

Capillary column DB-23 (60 m × 0.25 mm i.d. × 0.25 µm film thickness) - Carrier gas was nitrogen - Split flow at 86.3 mL/min - Temperatures were 300 °C for detector, 260 °C for injector, and 270 °C for column temperature. For FA identification, FAME Mix Supelco 37 Component, purchased from Sigma Aldrich (Darmstadt, Germany) was used as standards.

PHYSICAL ANALYSIS

COLOR AND YELLOW INDEX (YI) ASSESSMENT

Two forms of SB were subjected to color assessment according CIE Lab colour system (L*a*b*) using a colorimeter (Color Flex, HunterLab EZ model 45/0 LAV; Kruikebe associates laboratory, Elscolab, Belgium). At first, the raw material collected was used as such without prior treatment. Before reading, the butter was stored in a refrigerator at +/- 4 °C and maintained at room temperature for approximately 30 min. Then, each sample was melted in an oven and keep at + 40 °C before analysis to obtain liquid form. Sample was transferred to a glass cell, and color measurements were performed at different points of each disk according Lovi-bond color system L* (white to black) a* (red to green) b* (yellow to blue). Yellow index determination was optimized according to Pagliarini et al. [35] for solid and liquid SB, and value was calculated according Eq. (1) as follow:

$$Yellowness\ Index\ =\ 142{,}86\ b/L \quad (1)$$

With b = color yellow to blue value; L = color white to black value.

DETERMINATION OF SOLID FAT CONTENT BY *p-NMR*

Shea butter SFC determination was performed according to the (IUPAC 2.150) (a) non-tempered and (b) tempered serial methods [36] using a pulsed nuclear magnetic resonance (*p-NMR*) spectrometer (Minispec-mq20, Bruker, Karlsruhe, Germany). Analyses were done in duplicate per sample and values were recorded as the mean ± SD.

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THERMAL ANALYSIS BY DIFFERENTIAL SCANNING CALORIMETRY (DSC)

DSC analyze were performed according to the (AOCS Cj 1—94) method [3 3], using a TA DSC Q2000, (TA instruments, New Castle, DE, USA) equipped with a refrigerated cooling system. Sample was weighted between 4 and 6 mg and hermetically sealed in Tzero aluminium pan. An empty pan was used as a reference. The following characteristics were determined: fusion profile, crystallization profile, and enthalpy of fusion. Universal TA Analysis V4.5 A, TA Instruments was used to integrate DSC curves.

STATISTICAL ANALYSES

Data are expressed as mean with the corresponding standard deviation. Analysis of variance was used to determine the effect of extraction processes on the SB quality characteristics. Software RStudio (version 2023.06.1; Free Software Foundation, Inc) was used to performed multivariate analyzes, then principal components analysis (PCA) and clustering were used to classify crude SB according to their extraction processes, origin and physicochemical proper-ties. The relationships between DSC thermogram and standard chemical characteristics were determined by Pearson's correlation analysis using software RStudio.

Results and Discussion

SHEA BUTTER EXTRACTION PROCESSES IN BURKINA FASO

Shea butter extraction processes in Africa could be summarized in 6 steps [4]: (i) fruits getting - (ii) fruits pretreatment - (iii) nuts pretreatment - (iv) kernels pretreatment - (v) paste treatment - and (vi) emulsion/butter treatment. The major steps of the extraction process applied for the 37 investigated samples from Burkina Faso are shown in Table 2, regrouping the six main steps: (a) fruits post-harvesting and pre-treatment - (b) nuts pre-treatment - (c) kernels treatment - (d) paste processing - (e) emulsion treatment - and (f) end of extraction. In general, the SB production steps in Burkina Faso (Table 2) are not different from those previously defined by Goumbri et al. [4]., The extraction process in Northen Ghana involves five major steps [37]: weighing, sorting, washing and cleaning kernels; kernels crushing and roasting; crushed kernels milling/grinding into paste and kneading/beating; boiling of crude butter paste and filtration to obtain the shea oil; and solidification/cooling and packaging of fat. The six steps described in our study are not very different from those in Ghana, suggesting cross-border practices in SB production. Similar to Burkina Faso, both manual and semi-mechanized processes are used in Northen Ghana to extract SB. These processes require four major inputs: kernel, water, energy, and time [37]. To maximize profits, it is recommended to use these inputs more efficiently. This similarity in extraction processes across borders highlights the shared traditional knowledge and practices in the region, while also pointing to areas for potential improvement in efficiency and quality.

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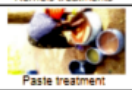
Semi-mechanized extraction involves equipment such as solar dryers or oven dryers for nuts and kernels treatment; crusher, roaster and grinder for kernels treatment; mixer system, churning machine, solar dryer and semi-mechanical oven; mixer, cooking oven, and vacuum filter for emulsion treatment. A closed semi-mechanized system is necessary to do hot packaging of butter. Investigated samples are described in Table 3, according to butter origin and type of extraction processes.

***Table 2**. (a) steps of several extraction processes of shea butter from Burkina Faso. (b) steps of several extraction processes of shea butter from Burkina Faso*

Processes steps		Process1															
		Kadi$_2$	Boul$_1$	Oubr$_1$	Como$_2$	Gour$_1$	Ioba$_2$	Koul$_1$	Baze$_1$	Naho$_1$	Boulg$_1$	Koul$_2$	Como$_2$	Houe$_1$	Houe$_2$	Houe$_3$	Houe$_4$
 Shea tree and Shea leaves	Post harvesting						x	x	x	x	x	x	x	x	x	x	x
	Sorting and washing						x			x	x						
	depulping						x	x	x	x	x	x	x	x	x	x	x
	Soaking																
	Sun drying						x										
 Nuts treatment	Nuts purchassing	x	x	x	x	x			x		x		x				
	Sorting and washing	x	x	x		x	x		x		x		x	x	x	x	x
	Sun drying	x	x			x			x								
	Boiling						x	x		x	x	x	x	x	x	x	x
	Sun drying						x	x		x	x	x	x	x	x	x	x
	Shelling	x	x	x	x	x	x	x	x	x	x	x					
	Sun drying			x	x												
	Oven drying																
	Sorting and washing												x	x	x	x	x
	Shelling												x	x	x	x	x
 Kernels treatments	Sorting and washing		x	x	x			x		x	x	x	x				
	Sun drying			x				x		x	x	x					
	Oven drying																
	Crushing	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Sun drying							x									
	Roasting	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
 Paste treatment	Milling	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Roasting																
	Kneading					x											
	Churning	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Boiling																
 Emulsion treatment	Washing					x	x	x	x	x	x		x	x	x	x	x
	Boiling	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x
	Filtering		x	x		x						x					
	Washing																
	Cooling		x				x		x				x				
	Water adding							x	x								
	Kneading							x									
	Cooling							x									
	Boiling					x		x	x	x	x	x					
 Crude butter	Cooling		x														
	Filtering					x	x		x	x	x	x	x				
	Kneading			x	x	x		x	x		x	x		x	x	x	x
	Filtering	x						x						x	x	x	x
	Packaging	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x

Processes steps		Process1									Process2			Process3		Process4	Process5
		Kene$_1$	Noum$_1$	Como$_1$	Como$_4$	Siss$_2$	Sang$_2$	Kadi$_1$	Naho$_2$	Naho$_3$	Houe$_3$	Komo$_1$	Ioba$_1$	Mouh$_1$	Siss$_1$	Yate$_1$	Naya$_1$
 Shea tree and Shea leaves	Post harvesting	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
	Sorting and washing			x	x				x		x						
	depulping	x	x	x	x	x	x	x	x	x	x		x		x		
	Soaking													x	x	x	x
	Sun drying				x												
 Nuts treatment	Nuts purchassing					x		x		x			x		x		
	Sorting and washing	x	x			x	x	x		x							x
	Sun drying									x			x				x
	Boiling	x	x	x	x	x	x	x	x		x	x			x	x	
	Sun drying	x	x	x	x	x	x	x	x			x				x	
	Shelling		x	x	x	x	x	x		x		x				x	
	Sun drying										x			x	x		
	Oven drying													x			x
	Sorting and washing	x	x			x			x	x	x		x				
	Shelling	x							x		x		x	x	x		x
 Kernels treatments	Sorting and washing			x	x		x	x			x			x	x		
	Sun drying			x	x			x			x						
	Oven drying													x			x
	Crushing	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x
	Sun drying																
	Roasting	x	x	x	x	x		x	x	x	x	x	x		x	x	
 Paste treatment	Milling	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x
	Roasting						x										
	Kneading										x	x					
	Churning	x	x	x	x	x	x	x	x	x	x		x	x	x		x
	Boiling										x	x	x			x	x
 Emulsion treatment	Washing	x	x		x	x	x	x	x	x			x	x	x		
	Boiling	x	x	x	x	x	x	x	x	x		x	x			x	x
	Filtering		x					x			x		x				
	Washing													x			
	Cooling			x				x		x	x						
	Water adding				x	x		x	x	x							
	Kneading			x				x									
	Cooling				x										x	x	x
	Boiling			x	x	x	x	x	x	x	x			x	x		
 Crude butter	Cooling				x			x						x			
	Filtering			x	x		x				x						
	Kneading	x		x	x	x	x		x	x				x	x		
	Filtering	x				x			x	x					x		
	Packaging	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x

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***Table 3**. Distribution of shea butter samples collected in Burkina Faso based on their locality and various extraction processes*

N°	Region	Province	Locality	Sample	Type of extraction process	
2	Midwest	Boulkiemdé	Koumlela	*Boul$_1$(b)*	Churning-Emulsion boiling	Process1
35		Sissili	Boura	Siss$_1$	Nuts soaking-Oven drying	Process3
36		Sissili	Léo	*Siss$_2$(b)*	Churning-Emulsion boiling	Process1
34		Sanguié	Réo	*Sang$_1$(b)*	Churning-Emulsion boiling	Process1
15	South West	Ioba	Dano	Ioba$_1$	Paste boiling	Process2
16				Ioba$_2$	Churning-Emulsion boiling	Process1
32		Noumbiel	Legmoin	*Noum$_1$(b)*	Churning-Emulsion boiling	Process1
17	Center	Kadiogo	Ouagadougou	*Kadi$_1$(b)*	Churning-Emulsion boiling	Process1
18				Kadi$_2$	Churning-Emulsion boiling	Process1
19				Kadi$_3$(a)	Unknown process	Unknown process
20				Kadi$_4$(a)	Unknown process	Unknown process
21				Kadi$_5$(a)	Unknown process	Unknown process
22				Kadi$_6$(a)	Unknown process	Unknown process
4	Cascades	Comoé	Banfora	*Como$_1$(b)*	Churning-Emulsion boiling	Process1
5		Comoé	Banfora	Como$_2$	Churning-Emulsion boiling	Process1
6		Comoé	Banfora	*Como$_3$(b)*	Churning-Emulsion boiling	Process1
7		Comoé	Noumoudara	Como$_4$	Churning-Emulsion boiling	Process1
1	Center-South	Bazèga	Diamkité	*Baze$_1$(b)*	Churning-Emulsion boiling	Process1
28		Nahouri	Pô	*Naho$_1$(b)*	Churning-Emulsion boiling	Process1
29		Nahouri	Pô	*Naho$_2$(b)*	Churning-Emulsion boiling	Process1
30		Nahouri	Pô	*Naho$_3$(b)*	Churning-Emulsion boiling	Process1
9	Upper-Basin	Houet	Bobo-ioulasso	*Houe$_1$(b)*	Churning-Emulsion boiling	Process1
10		Houet	Bobo-ioulasso	*Houe$_2$(b)*	Churning-Emulsion boiling	Process1
11		Houet	Péni	Houe$_3$	Churning-Emulsion boiling	Process1
12		Houet	Toussiana	Houe$_4$	Churning-Emulsion boiling	Process1
23		Kénédougou	Orodara	*Kene$_1$(b)*	Churning-Emulsion boiling	Process1
13		Houet	Bobo-Dioulasso	*Houe$_5$(b)*	Paste boiling	Process2
14				Houe$_6$(a)	Unknown process	Unknown process
33	Central Plateau	Oubritenga	Ziniaré	Oubr$_1$	Churning-Emulsion boiling	Process1
25	Center-East	Koulpélogo	Ouargaye	Koul$_1$	Churning-Emulsion boiling	Process1
3		Boulgou	Tenkodogo	*Boulg$_1$(b)*	Churning-Emulsion boiling	Process1

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26		Koulpélogo	Ouargaye	$Koul_2$	Churning-Emulsion boiling	Process1
37	North	Yatenga	Ouahigouya	$Yate_1$	Nuts soaking-Sun drying-Paste boiling-No churning	Process4
8	East	Gourma	Fada N'Gourma	*$Gour_1$(b)*	Churning-Emulsion boiling	Process1
24		Komondjari	Gayéri	$Komo_1$	Paste boiling	Process2
27	Mouhoun Loop	Mouhoun	Massala	$Mouh_1$	Nuts soaking-Oven drying	Process3
31		Nayala	Toma	$Naya_1$	Nuts soaking-Oven drying-Paste boiling	Process5

(a): Samples collected without knowing the type of extraction process; (b) semi-mechanized process. Samples numbers have been assigned in alphabetical order

QUALITY CHARACTERISTICS AND FATTY ACIDS DETERMINATION

QUALITY CHARACTERISTICS

Results of the chemical characterizations of the 37 samples are shown in Table 4. Statistical analyses were performed at 95% confidence level. The FFA content, expressed as oleic acid content (and SD), is a key quality indicator. In our study, the FFA content ranged from 1.1%±0.1%—9.7% ± 0.1%. The minimum value of 1.1% ± 0.1% indicates the potential for producing high-quality SB with low FFA content under optimal conditions. However, the maximum value is significantly higher than values (3.27%) reported by Seweh et al. [38] for SB from Ghana extracted using a mini automatic seed oil expeller in China. Seweh et al. [39] further reported FFA values of 5.25—5.59%, 4.65—4.73%, and 7.26—7.96% for SB from different regions of Ghana, extracted by traditional, mechanical, and chemical methods, respectively. These values are similarly high, consistent with our findings. However, Adel et al. [40] reported an even higher FFA content of 12.24% ± 0.30% for SB imported from Ghana. These differences may be attributed to various factors, including fruit ethnovarieties, nut and kernel treatment, extraction methods, and storage conditions.

In our study, sample Yate1 from process4 (no churning step, no double cooking of the emulsion, and no filtering of the emulsion) had the highest FFA content, unlike samples of process1 which had the lowest content. These results are similar to values reported for samples from Ghana and Benin [1, 38]. The boiling of kernels in water could lead to the breakdown of TAG, which responsible for the release of FFA, and uncontrolled cooking conditions could be responsible for the high levels measured in some samples.

An uncontrolled and non-standardized extraction technique could be responsible for high FFA content in some samples. The variation in FFA content highlights the need for standardized processing methods to enhance the quality and consistency of SB. According to FAO and NBF regional standards [20, 21], the samples analyzed in this study met the quality criteria (see Table 1) for food and soap manufacturing but did not meet the standards for the cosmetic/ pharmaceutical industry. FFA is a crucial indicator of the condition and edibility of the fat [40]. The levels of FFA can be reduced by neutralization or physical refining, but these procedures also reduce the content of several bioactive compounds naturally present in the SB. Therefore, it is advisable to keep the levels of FFA to a minimum by applying appropriate treatment practices.

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By applying Wijs method, IV obtained ranged from 54.0 ± 0.7 gI_2/100 g to 65.5 ± 0.3 gI_2/100 g, all within specification established by the Codex Alimentarius [20] (30 gI_2/100 g -75 gI_2/100 g). The IV is directly related to the degree of the oil unsaturation. Regarding crude SB, IV_{wijs} is slightly higher than IV_{GC}, due to the presence of kariten, which significantly influences the IV content. Therefore, it is recommended to calculate the IV based on FA composition (IV_{GC}, shown in Table 4). Thus, the calculated IV_{GC} ranged between 50.5 and 64.2, providing further accuracy to our understanding of the degree of unsaturation in the FA profile within the samples. Our findings are comparable to those reported for SB from Nigeria, extracted using traditional (61.90 gI_2/100 g), solvent (70.30 gI_2/100 g), enzymatic (67.28 gI_2/100 g), and mechanical (58.50 gI_2/100 g) methods [41]. However, the IV range observed for the samples in our study was slightly wider than the one (45.67 gI_2/100 g to 63.89 gI_2/100 g) by Seweh et al. [39] for SB from Ghana, extracted by traditional method, while it was lower compared to the range reported by Ossou et al. [42] for SB extracted through cold press (28.74 gI2⁄100 g), solvent (32.36 gI_2/100 g), and traditional (44.52 gI_2/100 g) methods. These differences are primarily related to variations in the FA composition of the fats. Indeed, a higher IV corresponds to a higher unsaturated FA content.

The PV is a valuable indicator of oil and fat quality, as it provides a measure of the level of rancidity. Peroxide value of SB obtained in this study ranged from 4.6 ± 0.1 $mEqO_2$/kg to 44.5 ± 0.2 $mEqO_2$/kg. According to F.A.O [20], among the 37 samples, 10 were classified as grade 1^b [11—15 $mEqO_2$/kg], making them suitable for food and cosmetic uses. Samples with PV greater than 15 $mEqO_2$/kg indicate poor-quality and are suitable for soap production. On the other hand, 9 samples met the criteria for grade 1^a (content less than 10 $mEqO_2$/kg) and are recommended for direct consumption [20]. These butters are also suitable for the cosmetics and pharmaceutical industries. Seweh et al. [39] showed that PV for SB extracted using traditional methods ranged from 3.25 $mEqO_2$/kg to 3.85 $mEqO_2$/kg, which is lower than the values found in our study. Ajala et al. [41] reported PV for SB extracted in Nigeria using traditional, solvent, enzymatic, and mechanical methods, which were 9.80 $mEqO_2$/kg, 11.00 $mEqO_2$/kg, 12.10 $mEqO_2$/kg, and 13.80 $mEqO_2$/kg, respectively. These values are also lower than most of our results. Similarly, for SB from Ivory Coast, PV were 2.28 mEq/kg for cold press, 1.88 mEq/kg for solvent extraction, and 2.94 mEq/kg for traditional methods [42]. These differences could be attributed to variations in the quality of raw materials, extraction methods, packaging, and storage conditions. In our study, samples with an unknown process had the lowest value, while the sample from process5 ($Naya_1$) had the highest value, followed by samples $Como_4$ (process1) and $Mouh_1$ (process3). Regarding nuts treatment, process5 is characterized by nuts sorting and washing before sun-drying followed by oven-drying. Then, kernels were oven-drying before crushing. Thus, our findings highlight the importance of optimizing raw material quality, extraction techniques, and processing conditions to produce high-quality SB with low PV. Ensuring better control over these factors can lead to more stable and high-quality SB suitable for various applications, including cosmetics and pharmaceuticals.

The measurement of specific extinction Kλ at 232 nm provides information about the content of conjugated FA dienes and primary oxidation products in the oil. Similarly, the Kλ at 268 nm provided data about conjugated trienes and secondary oxidation products. The ultraviolet absorbance coefficients provides oxidation products content in oils [43-45]. In our study, results for Kλ at 232 nm

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ranged from 0.61 to 1.34, while those for Kλ at 268 nm ranged from 2.92 to 5.69. The ΔK values fell within the range of 0.08 to 0.20. Specifications for Kλ at 232 nm and 268 nm, as well as ΔK, have been established for certain fats and oils, such as olive oil and olive-pomace oil, by the International Olive Council [46]. However, no specific specifications are available for SB. Sample $Como_2$ (process1) exhibited the lowest values for Kλ at 232 nm (0.612) and Kλ at 268 nm (2.916). However, sample $Houe_4$ (process1) showed the lowest ΔK value of 0.083, followed closely by $Como_2$ with a ΔK value of 0.084. On the other hand, Samples $Naho_3$ (process1) and $Kadi_4$ (unknown process) exhibited the highest Kλ at 232 nm values, reaching 1.337 and 1.244, respectively. Process1 seems to have effect on specific extinction. For Kλ at 268 nm and ΔK, sample $Kadi_4$ showed the highest values, measuring 5.685 and 0.201 respectively. These findings highlight the need for targeted improvements in the processing and storage conditions of SB to minimize oxidation. Reducing exposure to heat, light, and air during extraction and storage could quality criteria of crude SB.

The UMC ranged from 3.0%±1.0%—12.0%±0.1%. These values meet the specifications established by the F.A.O. [20], with the highest observed value being lower than the international standard limit of 19% (w/w). The high UMC is a critical factor for the interest in SB within the cosmetic and pharmaceutical industries, as it is higher than that found in other vegetable oils. This makes SB from Burkina Faso a valuable raw material for these industries. The high UMC values indicate that SB contains significant amounts of bioactive components, such as antioxidants, antimicrobials, anti-inflammatory substances, minerals, and vitamins [40]. Our findings are consistent with those from Abagale et al. [29], who reported UMC values ranging from 5.04% ± 0.04%—7.89% ± 0.02% in samples from Ghana. In contrast, Megnanou and Niamke [47] found even higher UMC values in beige and yellow SB, at 17.6% ± 0.1% and 17.3% ± 0.1%, respectively. According to Abagale et al. [29], the UMC does not depend on extraction processing, but rather on the environment in which the shea tree grew and the individual genetic makeup of the trees [29].

In general, the quality of the finished product is influenced by the quality of the raw materials. According to Womeni et al., [48], kernels thickness more than 10 mm, and sun-dried for more than 5 days, gave higher PV for SB from Cameroon. Kernels crushing enhances moisture evaporation, resulting in more acidity and lower UMC, triterpenic alcohols and sterols, due to an increasing contact surface area between enzymes and substrates. A prolonged sun exposure of the kernels leads to the formation of peroxides destabilizing the compounds with high melting point and poor stability. In our study, the significant variability observed in the chemical quality could be explained by the different varieties of shea fruits from Burkina Faso, as described by Sandwidi et al. [49]. The author identified 13 ethnovarieties of shea fruits, classifying them into four groups: pulp/flesh fruits, fruits with a high yield of kernel butter, pulp and butter fruits, and edible pulp fruits. According to Seweh et al. [39], SB from different geographical locations in Ghana showed significant chemical differences when extracted by different processes (chemical, mechanical, and traditional), which aligns with our findings. Additionally, the uncontrolled processes contribute to the variability in chemical quality.

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***Table 4**. Chemical characteristics of crude shea butter*

Sample	Peroxide value ($mEqO_2/kg$)	Free Fatty Acids (%)	Iodine value by Wijs (g/100 g)	Iodine value by GC (g/100 g)	Unsaponifiable matter content (%)	$K_{\lambda 232}$ nm	$K_{\lambda 268}$ nm	ΔK
$Baze_1$	14.5 ± 0.1	1.5 ± 0.1	58.8 ± 0.1	53.6	5.9 ± 2.6	0.759 ± 0.034	4.004 ± 0.004	0.122
$Boul_1$	19.6 ± 6.9	3.0 ± 0.1	55.2 ± 0.9	53.5	8.3 ± 0.1	1.057 ± 0.117	4,440 ± 0.082	0.123
$Boulg_1$	14,7 ± 0.1	1.7 ± 0.1	59.3 ± 0.2	54.3	8.5 ± 1.2	0.835 ± 0.001	4.222 ± 0.025	0.124
$Como_1$	14.8 ± 0.2	2.9 ± 0.1	56.5 ± 0.2	53.9	5.67 ± 1.4	0.740 ± 0.012	3.431 ± 0.008	0.099
$Como_2$	22.1 ± 3.4	6.1 ± 0.1	55.4 ± 0.3	53.9	3.9 ± 0.01	0.612 ± 0.001	2.916 ± 0.016	0.084
$Como_3$	19.9 ± 0.1	5.0 ± 0.1	55.9 ± 0.2	52.7	5.2 ± 0.2	0.828 ± 0.042	3.623 ± 0.034	0.100
$Como_4$	42.2 ± 3.8	6.3 ± 0.1	55.4 ± 0.1	54.3	5.1 ± 0.3	1.051 ± 0.090	4.111 ± 0.104	0.105
$Gour_1$	9.9 ± 0.1	3.9 ± 0.1	61.5 ± 0.9	54.3	7.6 ± 0.1	0.810 ± 0.009	3.845 ± 0.025	0.112
$Houe_1$	9,9 ± 0.1	3.5 ± 0.1	58.4 ± 0.2	54.8	6.4 ± 1.3	1.077 ± 0.007	4.821 ± 0.009	0.139
$Houe_2$	41.9 ± 3.0	2.1 ± 0.1	58.3 ± 0.7	53.9	4.8 ± 0.1	1.186 ± 0.138	4.970 ± 0.137	0.136
$Houe_3$	19.8 ± 6.9	1.1 ± 0.1	57.4 ± 0.7	53.9	5.8 ± 0.1	0.769 ± 0.029	3.137 ± 0.064	0.088
$Houe_4$	12.3 ± 3.5	4.9 ± 0.1	65.5 ± 0.3	64.2	5.2 ± 0.1	0.783 ± 0.030	3.305 ± 0.032	0.083
$Houe_5$	14.5 ± 0.1	4.5 ± 0.1	60.2 ± 0.4	55.6	6.9 ± 0.9	1.182 ± 0.012	5.028 ± 0.014	0.131
$Houe_6$	9.9 ± 0.1	5.0 ± 0.1	57.3 ± 0.8	54.8	3.7 ± 0.2	0.874 ± 0.074	3.570 ± 0.054	0.097
$Ioba_1$	14.9 ± 0.1	3.6 ± 0.1	58.2 ± 0.2	54.0	6.9 ± 0.1	0.719 ± 0.015	3.785 ± 0.006	0.111
$Ioba_2$	7.4 ± 3.5	2.1 ± 0.1	57.1 ± 0.6	53.0	6.8 ± 1.4	0.672 ± 0.004	3.669 ± 0.025	0.105
$Kadi_1$	9.9 ± 0.1	5.3 ± 0.1	60.2 ± 0.3	52.6	7.0 ± 0.1	0.645 ± 0.025	3.500 ± 0.067	0.104
$Kadi_2$	9.9 ± 0.1	8.2 ± 0.1	55.2 ± 0.5	54.2	7.0 ± 0.1	1.227 ± 0.133	5.384 ± 0.085	0.148
$Kadi_3$	22.3 ± 3.3	4.3 ± 0.1	58.7 ± 0.3	53.0	6.9 ± 0.3	0.941 ± 0.023	4.200 ± 0.031	0.122
$Kadi_4$	6.1 ± 1.7	2.7 ± 0.1	56.5 ± 1.2	53.8	7.9 ± 0.1	1.244 ± 0.006	5.685 ± 0.040	0.201
$Kadi_5$	4.6 ± 0.1	2.5 ± 0.1	58.8 ± 0.5	54.7	6.0 ± 0.1	1.131 ± 0.193	3.534 ± 0.204	0.159
$Kadi_6$	19.7 ± 0.1	4.1 ± 0.1	57.8 ± 0.1	54.4	6.0 ± 1.8	1.188 ± 0.037	5.480 ± 0.117	0.149
$Kene_1$	27.1 ± 3.5	6.0 ± 0.4	58.2 ± 0.6	55.4	3.0 ± 1.0	0.751 ± 0.070	3.034 ± 0.055	0.091
$Komo_1$	34.3 ± 0.1	2.8 ± 0.1	56.9 ± 0.7	53.2	5.6 ± 0.1	0.765 ± 0.008	3.745 ± 0.032	0.109
$Koul_1$	22.1 ± 3.5	2.4 ± 0.1	58.0 ± 0.1	53.8	12.0 ± 0.1	1.012 ± 0.027	4.699 ± 0.022	0.136
$Koul_2$	31.89 ± 3.5	2.5 ± 0.1	61.5 ± 0.2	55.7	6.6 ± 0.8	0.797 ± 0.011	4.088 ± 0.014	0.134
$Mouh_1$	37.0 ± 3.4	1.1 ± 0.1	57.7 ± 0.4	54.6	9.3 ± 0.1	0.998 ± 0.037	3.652 ± 0.032	0.100
$Naho_1$	24.4 ± 0.2	3.0 ± 0.2	60.0 ± 0.2	54.4	7.4 ± 0.1	1.024 ± 0.110	4.352 ± 0.094	0.122
$Naho_2$	9.8 ± 0.1	2.2 ± 0.1	56.4 ± 0.8	53.7	7.6 ± 0.1	0.911 ± 0.016	4.155 ± 0.017	0.118
$Naho_3$	14.8 ± 0.1	3.1 ± 0.1	60.1 ± 0.7	55.2	8.0 ± 0.1	1.337 ± 0.137	4.776 ± 0.117	0.130
$Naya_1$	44.5 ± 0.2	2.6 ± 0.1	58.9 ± 0.7	53.5	7.9 ± 0.1	0.938 ± 0.045	4.384 ± 0.014	0.127
$Noum_1$	24.8 ± 0.1	2.4 ± 0.1	54.8 ± 0.2	53.1	5.4 ± 0.1	0.677 ± 0.040	3.392 ± 0.019	0.097

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$Oubr_1$	20.0 ± 0.1	2.0 ± 0.1	54.0 ± 0.7	52.9	5.6 ± 0.1	1.093 ± 0.006	4.567 ± 0.011	0.119
$Sang_1$	29.5 ± 0.1	2.5 ± 0.1	55.9 ± 0.9	53.8	6.7 ± 0.7	0.823 ± 0.078	3.910 ± 0.036	0.114
$Siss_1$	14.9 ± 0.1	3.1 ± 0.1	61.3 ± 0.1	53.1	9.5 ± 0.1	1.213 ± 0.012	4.802 ± 0.031	0.136
$Siss_2$	14.8 ± 0.1	7.0 ± 0.1	56.2 ± 0.3	50.5	3.0 ± 1.0	0.794 ± 0.065	3.831 ± 0.078	0.111
$Yate_1$	12.2 ± 3.4	9.7 ± 0.1	58.5 ± 0.5	54.9	7.6 ± 0.1	0.775 ± 0.013	3.712 ± 0.008	0.105

Analyses were done in triplicate per sample and values were recorded as the mean ± SD

CRUDE SHEA BUTTER FATTY ACIDS PROFILE

The results of FA analysis are shown in Table 5. Stearic acid (C18:0) and oleic acid (C18:1) were the major FA, ranging from 33.9%±0.1%—47.2%±0.2% and from 40.8%±0.2%—51.0%±0.1%, respectively. Linoleic acid (C18:2) was the predominant polyunsaturated fatty acid (PUFA), ranging from 5.8%±0.1 to 8.4%±0.1%. The FA composition of SB from Burkina Faso falls within the appropriate ranges defined by the Codex Alimentarius [20], indicating the good quality of the samples. This pure butter could be processed locally and/or exported. In general, the FA contents of SB from Burkina Faso are similar to the values obtained in Ghana and Ivory Coast, as described by some authors [38, 43]. Davrieux et al. [27] reported that shea trees in West Africa consistently produce butter with high stearic acid and low oleic acid content. Typically, SB from East Africa (Ethiopia, South Sudan, Uganda, Democratic Republic of Congo), which comes from the subspecies *nilotica*, has a higher oleic acid content compared to the subspecies *paradoxa* found in West and Central Africa [27, 50]. Furthermore, according to Vincenzo et al. [28], the average oleic acid content in samples from East Africa (Uganda) was about 58% with stearic acid at approximately 29%, whereas samples from West Africa (Burkina Faso and Mali) had oleic and stearic acids at approximately 43% and 44%, respectively. However, Maranz et al. [51] highlighted a very important fact. They reported that soft butters (with a higher content of oleic acid than stearic acid) appear to be predominant in all *V. paradoxa ssp. nilotica* distribution areas and some paradoxa zones. Thus, in the main West African production areas, such as Mali, Burkina Faso, Ivory-Coast, and Ghana, there are individual trees that produce soft butter. Currently, on the international market, exports of shea products (nuts and butters) are dominated by those from *Vitellaria paradoxa* populations. This is due to the composition of its butter, which is rich in stearic acid and ideally suited for the chocolate and confectionary industries.

In our study, sample $Houe_4$, obtained through the process of boiling nuts, sun-drying, roasting kernels, milling and churning paste, followed by emulsion washing and boiling, had the lowest stearic acid value and the highest values for palmitic and linoleic acids. However, samples from process1 ($Kadi_1$) and process3 ($Siss_2$) exhibited the lowest values for palmitic acid and linoleic acid, respectively. The extraction steps of these samples, involving double-boiling of the emulsion, differed from those of sample $Houe_4$. Three samples obtained from process1 ($Como_3$, $Kadi_1$, and $Siss_2$) showed the highest values for stearic acid. Linoleic acid was reported as the main FA, ranging from 57,8% to 68,0%, followed by stearic acid, 22.5-28.9% in Uganda (East Africa) [1]. This is most

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probably due to the different sub-species: *Vittelaria paradoxa nilotica*, is the sub-specie which grow in East Africa, unlike *V. paradoxa paradoxa* in West Africa.

***Table 5**. Profile of the major fatty acids (in % content) of crude shea butter samples collected in Burkina Faso*

Sample	Palmitic acid (C16:0)	Stearic acid (C18:0)	Oleic acid (C18:1)	Linoleic acid (C18:2)	Gadoleic acid (C20:1)
Baze$_1$	3.3 ± 0.1	43.5 ± 0.1	44.4 ± 0.1	5.9 ± 0.1	1.6 ± 0.1
Boul$_1$	3.3 ± 0.1	44.0 ± 0.1	44.0 ± 0.1	6.0 ± 0.1	1.6 ± 0.1
Boulg$_1$	3.6 ± 0.1	43.8 ± 0.1	43.2 ± 0.1	6.9 ± 0.1	1.7 ± 0.1
Como$_1$	3.4 ± 0.1	43.4 ± 0.1	44.9 ± 0.1	6.1 ± 0.1	1.4 ± 0.1
Como$_2$	3.2 ± 0.1	43.4 ± 0.1	44.7 ± 0.1	6.0 ± 0.1	1.6 ± 0.1
Como$_3$	3.2 ± 0.1	44.8 ± 0.1	43.9 ± 0.1	5.8 ± 0.1	1.6 ± 0.1
Como$_4$	3.2 ± 0.1	43.0 ± 0.1	45.0 ± 0.1	6.1 ± 0.1	1.5 ± 0.1
Gour$_1$	3.6 ± 0.1	42.7 ± 0.1	45.2 ± 0.1	6.0 ± 0.1	1.3 ± 0.1
Houe$_1$	3.1 ± 0.1	43.1 ± 0.1	44.9 ± 0.1	6.4 ± 0.1	1.6 ± 0.1
Houe$_2$	3.3 ± 0.1	43.4 ± 0.1	44.9 ± 0.1	5.9 ± 0.1	1.5 ± 0.1
Houe$_3$	3.3 ± 0.1	43.3 ± 0.1	44.9 ± 0.1	5.9 ± 0.1	1.5 ± 0.1
Houe$_4$	3.7 ± 0.1	33.9 ± 0.1	51.0 ± 0.1	8.4 ± 0.1	1.2 ± 0.1
Houe$_5$	3.2 ± 0.1	41.9 ± 0.1	45.8 ± 0.1	6.5 ± 0.1	1.5 ± 0.1
Houe$_6$	3.3 ± 0.1	42.3 ± 0.1	45.8 ± 0.1	6.0 ± 0.1	1.5 ± 0.1
Ioba$_1$	3.5 ± 0.1	43.4 ± 0.1	44.3 ± 0.1	6.2 ± 0.1	1.5 ± 0.1
Ioba$_2$	3.2 ± 0.1	44.8 ± 0.1	43.6 ± 0.1	6.1 ± 0.1	1.6 ± 0.1
Kadi$_1$	3.1 ± 0.1	45.1 ± 0.1	43.4 ± 0.1	5.8 ± 0.1	1.6 ± 0.1
Kadi$_2$	3.2 ± 0.1	43.5 ± 0.1	44.4 ± 0.1	6.20 ± 0.1	1.6 ± 0.1
Kadi$_3$	3.2 ± 0.1	44.4 ± 0.1	44.1 ± 0.1	5.9 ± 0.1	1.6 ± 0.1
Kadi$_4$	3.4 ± 0.1	43.6 ± 0.1	44.1 ± 0.1	6.2 ± 0.1	1.6 ± 0.1
Kadi$_5$	3.3 ± 0.1	42.5 ± 0.1	44.8 ± 0.1	6.3 ± 0.1	1.6 ± 0.1
Kadi$_6$	3.3 ± 0.1	43.0 ± 0.1	44.7 ± 0.1	6.3 ± 0.1	1.5 ± 0.1
Kene$_1$	3.2 ± 0.1	42.0 ± 0.1	46.5 ± 0.1	5.9 ± 0.1	1.4 ± 0.1
Komo$_1$	3.3 ± 0.1	44.0 ± 0.1	44.6 ± 0.1	5.8 ± 0.1	1.5 ± 0.1
Koul$_1$	3.6 ± 0.1	43.2 ± 0.1	44.8 ± 0.1	5.9 ± 0.1	1.6 ± 0.1
Koul$_2$	3.3 ± 0.1	41.7 ± 0.1	46.3 ± 0.1	6.2 ± 0.1	1.4 ± 0.1
Mouh$_1$	3.4 ± 0.3	42.7 ± 0.1	45.3 ± 0.2	6.2 ± 0.1	1.4 ± 0.1
Naho$_1$	3.4 ± 0.1	43.3 ± 0.1	45.0 ± 0.1	6.3 ± 0.1	1.5 ± 0.1
Naho$_2$	3.5 ± 0.1	43.5 ± 0.1	44.6 ± 0.1	6.1 ± 0.1	1.5 ± 0.1

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$Naho_3$	3.3 ± 0.1	42.6 ± 0.1	45.4 ± 0.1	6.5 ± 0.1	1.5 ± 0.1
$Naya_1$	3.6 ± 0.1	43.2 ± 0.1	44.6 ± 0.1	6.0 ± 0.1	1.5 ± 0.1
$Noum_1$	3.4 ± 0.1	44.6 ± 0.1	42.9 ± 0.1	6.4 ± 0.1	1.6 ± 0.1
$Oubr_1$	3.2 ± 0.1	44.7 ± 0.1	44.0 ± 0.1	5.9 ± 0.1	1.5 ± 0.1
$Sang_1$	3.4 ± 0.1	43.6 ± 0.1	44.2 ± 0.1	6.1 ± 0.1	1.6 ± 0.1
$Siss_1$	3.5 ± 0.1	44.3 ± 0.1	43.5 ± 0.1	6.2 ± 0.1	1.7 ± 0.1
$Siss_2$	3.4 ± 0.1	47.2 ± 0.2	40.8 ± 0.2	6.1 ± 0.1	1.5 ± 0.1
$Yate_1$	3.6 ± 0.1	42.6 ± 0.1	45.0 ± 0.1	6.4 ± 0.1	1.6 ± 0.1

Analyses were done in triplicate per sample and values were recorded as the mean ± SD

Physical Characteristics

SHEA BUTTER COLOR AND YELLOWNESS INDEX

Color values determined by Lovibond color (L*, a*, b*) system are presented in Table 6. Our findings indicate that solid forms of SB exhibited L* values ranging from 61.5 ± 0.1 to 82.0 ± 0.1. Specifically, samples $Gour_1$ from process1 and $Komo_1$ from process2 showed the highest Lightness (L*) values of 82.0 ± 0.1 and 81.0 ± 0.1, respectively. These samples originated from the East. Notably, $Houe_4$ (process1) from Upper-Basin and $Naya_1$ (process5) from Mouhoun Loop exhibited lower L* values. Unlike the other samples examined, $Naya_1$ undergoes settling without filtration, which is probably the reason for the observed differences. A study conducted in Ivory Coast found that artisanal SB samples exhibited color ranging from white, beige, to yellow [14]. Specifically, the L* values reported were between 63.66 ± 1.15 and 68.67 ± 0.58 for yellow "market" and yellow "original" butter, respectively. According to Kouame et al. [42], in a subsequent study conducted in Ivory Coast, SB extracted through cold press, solvent extraction, and traditional methods showed L* values of 37.18, 55.23, and 66.18, respectively. These findings are consistent with our results.

The yellow hue of SB is attributed to its carotenoid content. In its solid form, SB shows b* values (indicating yellow to blue) ranging from 13.3 ± 0.1 to 30.1 ± 0.1. These values vary slightly in its liquid form (from 12.8 ± 0.1 to 36.2 ± 0.1). Shea butter's brightness (L*) decreases with storage time and depends on the type of container used [52]. Our results indicate that melted samples appeared less shiny compared to unmeted ones, with an average ratio of approximately 0.78. The melting process significantly influenced the brightness of shea butter, with melted L* values ranging from 40.1 ± 0.1 to 66.9 ± 0.3. Specifically, the brightness ratio between melted and solid forms for $Naya_1$ was lower at 0.65, likely due to the absence of filtration. Filtration of the butter before packaging could potentially remove dissolved impurities, thereby improving its brightness. In both solid and liquid SB obtained through traditional extraction methods, the YI serves as an indicator of color changes. Our findings show that melted butter generally had higher YI values compared to the solid form. On average, the YI ratio was around 1.2 for all samples, with values ranging from 0.7 ($Houe_6$) to 2.5

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(Naya$_1$). In particular, Naya1 exhibited the lowest L* value, likely due to its extraction process which lacks filtration of the emulsion and butter before packaging (see Table 2).

***Table 6**. Crude and melted shea butter color (L*. a*, b*) system and yellow index*

Sample	L* (Crude)	L* (Melted)	a* (Crude)	a* (Melted)	b* (Crude)	b* (Melted)	YI (Crude)	YI (Melted)
Baze$_1$	76.6 ± 0.1	59.4 ± 0.2	-0.4 ± 0.1	-3.1 ± 0.1	29.4 ± 0.1	29.3 ± 0.1	54.8 ± 0.2	70.5 ± 0.4
Boul$_1$	76.0 ± 0.1	58.9 ± 0.2	-1.4 ± 0.1	-3.5 ± 0.1	23.7 ± 0.2	24.8 ± 0.1	44.6 ± 0.4	60.2 ± 0.4
Boulg$_1$	77.8 ± 0.1	65.4 ± 0.1	-1.0 ± 0.1	-2.7 ± 0.1	19.5 ± 0.1	12.9 ± 0.1	35.8 ± 0.1	28.2 ± 0.2
Como$_1$	78.9 ± 0.1	61.8 ± 0.1	-2.1 ± 0.1	-2.7 ± 0.1	20.5 ± 0.1	13.5 ± 0.1	37.1 ± 0.2	31.2 ± 0.1
Como$_2$	79.8 ± 0.2	58.6 ± 0.1	-1.8 ± 0.1	-4.3 ± 0.1	22.4 ± 0.1	20.4 ± 0.1	40.0 ± 0.2	49.6 ± 0.1
Como$_3$	80.2 ± 0.1	63.5 ± 0.1	-3.4 ± 0.1	-4.6 ± 0.1	24.4 ± 0.2	19.4 ± 0.1	43.4 ± 0.4	44.0 ± 0.1
Como$_4$	75.1 ± 0.1	62.1 ± 0.3	0.9 ± 0.1	-2.5 ± 0.1	23.6 ± 0.1	23.5 ± 0.1	44.8 ± 0.1	54.1 ± 0.5
Gour$_1$	82.0 ± 0.1	60.0 ± 0.1	-0.6 ± 0.1	-4.8 ± 0.1	24.7 ± 0.3	23.7 ± 0.1	43.0 ± 0.5	56.4 ± 0.2
Houe$_1$	73.9 ± 0.1	59.3 ± 0.2	1.3 ± 0.1	-2.0 ± 0.1	26.0 ± 0.3	25.5 ± 0.1	50.3 ± 0.6	61.4 ± 0.2
Houe$_2$	78.9 ± 0.1	61.8 ± 0.3	-0.2 ± 0.1	-3.5 ± 0.1	27.4 ± 0.2	23.5 ± 0.1	49.6 ± 0.3	54.2 ± 0.3
Houe$_3$	72.6 ± 0.2	55.1 ± 0.2	0.9 ± 0.1	-0.5 ± 0.1	19.0 ± 0.1	24.4 ± 0.1	37.3 ± 0.1	63.3 ± 0.5
Houe$_4$	67.4 ± 0.1	61.2 ± 0.2	2.1 ± 0.1	-1.7 ± 0.1	26.2 ± 0.1	30.4 ± 0.2	55.5 ± 0.2	71.1 ± 0.8
Houe$_5$	79.9 ± 0.1	61.3 ± 0.1	-1.7 ± 0.1	-3.1 ± 0.1	18.4 ± 0.1	21.9 ± 0.1	32.8 ± 0.2	51.1 ± 0.3
Houe$_6$	80.6 ± 0.1	62.6 ± 0.1	-1.0 ± 0.1	-3.3 ± 0.1	27.2 ± 0.2	15.2 ± 0.1	48.2 ± 0.3	35.0 ± 0.1
Ioba$_1$	78.1 ± 0.1	59.6 ± 0.3	-0.6 ± 0.1	-3.3 ± 0.1	24.2 ± 0.6	25.4 ± 0.2	44.3 ± 1.1	61.0 ± 0.8
Ioba$_2$	78.6 ± 0.1	64.2 ± 0.2	-1.5 ± 0.1	-3.4 ± 0.1	20.8 ± 1.3	18.9 ± 0.1	37.8 ± 2.2	42.1 ± 0.2
Kadi$_1$	76.2 ± 0.1	62.6 ± 0.1	-1.7 ± 0.1	-3.9 ± 0.1	23.3 ± 0.2	24.0 ± 0.1	43.7 ± 0.3	55.0 ± 0.2
Kadi$_2$	75.7 ± 0.1	61.6 ± 0.1	0.1 ± 0.1	-3.6 ± 0.1	25.5 ± 0.1	34.6 ± 0.1	48.1 ± 0.2	80.3 ± 0.3
Kadi$_3$	79.3 ± 0.1	62.9 ± 0.1	-1.5 ± 0.1	-3.5 ± 0.1	23.5 ± 0.3	17.1 ± 0.1	42.3 ± 0.6	38.8 ± 0.1
Kadi$_4$	77.7 ± 0.1	60.2 ± 0.2	-1.4 ± 0.1	-3.0 ± 0.1	21.2 ± 0.1	27.5 ± 0.1	38.9 ± 0.1	65.1 ± 0.2
Kadi$_5$	74.1 ± 0.1	61.1 ± 0.4	1.2 ± 0.1	-2.1 ± 0.1	23.9 ± 0.2	31.7 ± 0.2	46.1 ± 0.4	74.2 ± 0.8
Kadi$_6$	77.4 ± 0.1	64.9 ± 0.1	-2.3 ± 0.1	-5.5 ± 0.1	29.6 ± 0.1	29.9 ± 0.1	54.6 ± 0.1	65.8 ± 0.2
Kene$_1$	68.2 ± 0.1	59.6 ± 0.2	0.8 ± 0.1	-1.8 ± 0.1	21.9 ± 0.1	23.8 ± 0.2	45.8 ± 0.2	56.9 ± 0.5
Komo$_1$	81.0 ± 0.1	66.9 ± 0.3	-2.0 ± 0.1	-3.3 ± 0.1	18.7 ± 0.1	12.8 ± 0.1	33.0 ± 0.1	27.2 ± 0.2
Koul$_1$	76.1 ± 0.1	59.2 ± 0.1	-0.3 ± 0.1	-1.7 ± 0.1	13.3 ± 0.1	13.0 ± 0.1	24.9 ± 0.1	31.5 ± 0.3
Koul$_2$	79.7 ± 0.2	60.7 ± 0.5	-1.8 ± 0.1	-3.5 ± 0.1	23.1 ± 0.2	20.0 ± 0.1	41.4 ± 0.5	47.1 ± 0.3
Mouh$_1$	75.6 ± 0.1	60.7 ± 0.3	-0.1 ± 0.1	-2.3 ± 0.1	18.0 ± 0.5	20.8 ± 0.1	34.1 ± 1.1	49.0 ± 0.3
Naho$_1$	76.6 ± 0.1	59.6 ± 0.2	-1.5 ± 0.1	-3.1 ± 0.1	20.1 ± 0.1	20.7 ± 0.1	37.4 ± 0.1	49.5 ± 0.4
Naho$_2$	79.5 ± 0.1	60.7 ± 0.1	-1.1 ± 0.1	-2.4 ± 0.1	17.9 ± 0.2	14.9 ± 0.1	32.2 ± 0.4	35.0 ± 0.2
Naho$_3$	77.1 ± 0.2	55.8 ± 0.2	-2.0 ± 0.1	-2.4 ± 0.1	19.4 ± 0.4	21.7 ± 0.1	35.9 ± 0.8	55.5 ± 0.4
Naya$_1$	61.5 ± 0.1	40.1 ± 0.1	2.9 ± 0.1	6.1 ± 0.1	21.5 ± 0.1	36.2 ± 0.1	50.0 ± 0.2	128.8 ± 0.1

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$Noum_1$	75.3 ± 0.1	55.7 ± 0.1	1.4 ± 0.1	-0.9 ± 0.1	25.2 ± 0.2	33.2 ± 0.1	47.9 ± 0.4	85.2 ± 0.2
$Oubr_1$	80.0 ± 0.1	62.5 ± 0.1	-0.1 ± 0.1	-3.4 ± 0.1	30.1 ± 0.1	18.1 ± 0.1	53.7 ± 0.1	41.3 ± 0.1
$Sang_1$	80.8 ± 0.1	63.1 ± 0.3	-1.5 ± 0.1	-3.5 ± 0.1	24.1 ± 0.1	18.3 ± 0.1	42.7 ± 0.1	41.4 ± 0.3
$Siss_1$	76.1 ± 0.1	58.0 ± 0.2	-1.2 ± 0.1	-1.8 ± 0.1	14.8 ± 0.1	17.4 ± 0.1	27.9 ± 0.1	43.0 ± 0.2
$Siss_2$	77.8 ± 0.1	62.6 ± 0.2	-0.1 ± 0.1	-2.8 ± 0.1	22.2 ± 0.1	16.4 ± 0.1	40.7 ± 0.2	37.5 ± 0.2
$Yate_1$	71.8 ± 0.2	55.9 ± 0.2	-0.2 ± 0.1	-3.0 ± 0.1	28.4 ± 0.2	31.8 ± 0.1	56.5 ± 0.2	81.2 ± 0.4

Analyses were done in triplicate per sample and values were recorded as the mean ± SD

SHEA BUTTER SOLID FAT CONTENT (SFC)

Solid fat content (SFC) is a crucial parameter used to determine the suitability of an oil, fat, or blend for specific applications [53]. The SFC profiles of all the crude SB samples, measured by *pulsed NMR* are shown in Figure 2 using tempered b) and non-tempered a) methods. The 37 samples investigated exhibited varying SFC profiles depending on their origin and extraction processes. Without any tempering (Figure 2a and c), among all samples, $Siss_2$, $Kadi_1$, $Como_3$, $Ioba_2$, $Noum_1$ and $Oubr_1$, originating from different regions but obtained using the same extraction method (Process 1), exhibited higher SFC profiles compared to the others. In contrast, $Houe_4$ (process1), $Houe_5$ (process2) and $Kene_1$ (process1), originating from the same region showed the lowest SFC profiles. SB with a high content of saturated fatty acids (SAFA), especially high content of stearic acid and low content of unsaturated fatty acids, exhibited the highest SFC values. A higher stearic acid content increased the SFC profile, particularly in the range 20 to 35 °C. Especially, the oleic content of the samples $Oubr_1$ and $Ioba_2$ was about 44.0%, closer to the lowest content found in this study (41.0% for sample Siss2). Their IV_{GC} and FFA were also close to lower value, respectively 53.0 g/100 g and 2.02.1%. Thus, the highest SFC profiles observed for $Siss_2$, $Kadi_1$, $Como_3$, $Ioba_2$, $Noum_1$ and $Oubr_1$ are due to their high content of stearic acid (see Table 5). As reported by Kouassi et al. [54], data below room temperature (25 °C) indicates the firmness of the fat, whereas the SFC measured between 25 and 30 °C indicates its heat resistance. Samples $Siss_2$, $Kadi_1$, $Como_3$, $Ioba_2$, $Noum_1$ and $Oubr_1$ had the highest hardness, while $Houe_4$, $Houe_5$ and $Kene_1$ had the lowest one. These observations are consistent with the results of the IV analysis. The differences observed could lead to a wide range of applications in the food, pharmaceutical, and cosmetic industries. However, the complete melting of all samples occurs around 40 °C, which would lead to a waxy mouthfeel.

In general, the results demonstrated the relationship between fat composition (depending on origin and variety) and physical properties, and highlighted the impact of the extraction process on the physicochemical characteristics of SB from Burkina Faso.

During the tempering process, the fat crystals are converted to more stable polymorphs, leading to a narrow melting range. Like CB, SB is a polymorphic fat that must be tempered in order to achieve the desired properties. According to Gao et al. [55], tempering is essential to ensure the stability and quality of the final products and its widely applied to stabilize confectionary fats [56]. In our study, tempering at 26 °C had similar effect on the SFC profile of all the samples. Above 25 °C, SFC was

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shifted to higher values for all samples, indicating that polymorphic transitions occurred during the treatment.

SHEA BUTTER THERMAL BEHAVIOR BY DSC

The thermal behavior of all samples, during both crystallization (Figure 3a-c) and melting (Figure 4e-g), was also analyzed using DSC. The thermal characteristics such as crystallization onset temperature, complete melting temperature, the enthalpy of crystallization and melting, and the temperature of exothermic and endothermic transition peaks are showed in Table 7. The crystallization curves of all samples appeared relatively similar, and exhibiting four distinct exothermic transitions (c1, c2, (T_{Peak}), and c4 (T_{Onset})) (Figure 3f-h). The crystallization onset temperature ranged from 16.4°C to 22.4°C (Table 7). All thermograms were similar to that reported of SB from Ghana previously reported by Badu et al. [57], showing four transition peaks. However, the thermal curve is dependent on the scanning rate, regardless of the chemical composition of the fats [54]. This makes it difficult to compare results from other studies that use different scanning rates or calorimeters. The different crystallization behaviors of the SB investigated are due to the difference in FA content. Crystallization profile 1 differed from the other profiles by the shape of the curve at T_{Onset} (Figure 3a-b). All the extractions processes illustrated in Tables 2 and 3, were found in this profile. Analysis showed that profile 1 has higher transitions temperatures c4 (T_{Onset}) ranged between 17.7 to 22.4°C. This could be explained by the high level of SAFA content. Based on their extraction processes, the samples were diversely distributed among the three crystallization profiles identified in this study. This variation could be explained by the fact that the physical properties of fats, such as crystallization and melting behavior, are closely related to the FA composition, which is influenced by the extraction process used. Samples showing profile 1 were characterized by the highest levels of stearic acid, and the lowest levels of oleic acid ranged between 42.6%-47.2% and 40.8%-45.3% respectively. It is worth to mention that besides the difference FA profile, these samples possess the FFA and PV among the highest between 9.7% and 9.8-44.5mEqO_2/kg. Unsaponifiable matter content were diversely distributed in samples from profile 1, include the lowest (3.0%) and highest value (12.0%). Crystallization profile 2 (Figure 3c and d) exhibited many samples which were different from profile 1 in the shape of the peak at c4. Regarding profile 3, their samples differed to other samples by the shape of the curve in c', highlighted in the Figure 3e and g. Four regions, among the eleven were identified in this section, with two extraction processes (process1 and unknown process) and correspond to the samples with lowest stearic acid content and highest oleic acid content, respectively 33.9—43.3%, 44.8—51.0% contrary to profile type 1 and IV_{GC} higher values 54.3—64.2 g/100 g. Profile 3 was characterized by specific transitions temperatures c' (15.1 to 16.3 °C), identified between c3 and c4.

The DSC melting curves of the 37 samples of SB are showed in Figure 4. Three different parameters were measured by integration: melting enthalpy (Hf) of the first three peaks, Hf1, Hf2, Hf3 (J/g) and the total melting enthalpy (J/g) are shown in Table 7. Then, some ratio of enthalpy ΔHf, were calculated (ΔHf = Hf2/Hf3) in order to classify profiles. It can be noticed that ΔHf ranged between [0.51—0.95 J/g], [1.01—1.47 J/g], and [1.51—4.34 J/g]. Based on this classification, differences were

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found in the melting curves, highlighted 3 profiles: profile 1 (Figure 4a-c), profile 2 (Figure 4d), and profile 3 (Figure 4e). Overlapping analysis for thermal behavior shown 4 endothermal peaks: h1, h2 (T_{Onset}), h3 (T_{Peak}) and h4 (T_{End}), illustrated in Figure 4f-h, highlighted typical enthalpy of fusion resulting from samples $Sang_1$, $Como_4$ and $Como_3$. All melting curves were complex due the compositional diversity of SB. However, similarities were identified on the melting profiles of some samples which were grouped into three profiles (Figure 4a-e). This may be linked to the similarity in their fat composition. The classification of the samples from melting profiles was different to the one based on the crystallization profiles. This could be explained by the mode of classification applied, according to plots similarities for crystallization, and enthalpy for fusion. First, melting profile 1 included the great majority of samples with all the extraction processes shown in the Table 3, as well as all the origin except the Cascades region. This profile was made up of the samples with min and max values of FFA 1.0-9.7%, and PV 4.6-44.5 $mEqO_2/kg$. Transitions temperatures, T_{Peak} and T_{End} ranged between 12.1 and 14.7 °C, to 25.0—29.3 °C respectively. Transitions temperatures varied slightly between samples. The complete melting of the SB samples ranged from 38.4 °C to 43.1 °C. This is consistent with what was observed in SFC analysis without tempering. The DSC melting profiles of SB samples studied were different to that reported by Badu et al. [57] for SB from Ghana. As stated previously, this difference could be due to the variation in fat composition and the different scanning conditions. In our study the total melting enthalpy ranged from 62 to 73 J/g. Our results showed that for melting profile 2, only process1 and one of unknown process were included. Regarding melting profile 3, process1, process2 and unknown process were represented, closed to profile 2. The FA content for these two profiles were diversly distributed. Indeed, their transitions temperatures, T_{Peak} and T_{End} were closer and varied slightly.

In general, the results highlight the great diversity in thermal behavior observed across crude SB samples from Burkina Faso. This variability underscores the complex relationship between composition and thermal properties in SB, which can influence its suitability for various applications in food, pharmaceuticals, and cosmetics. Understanding these factors is crucial for optimizing processing methods and ensuring consistent product quality.

***Figure 2**. Solid fat content profiles of all crude shea butter samples obtained by p-NMR with non-tempered serial method (a), and tempered serial method (b). Samples with the highest and the lowest SFC profile according tempered and non-tempered methods are presented in (c)*

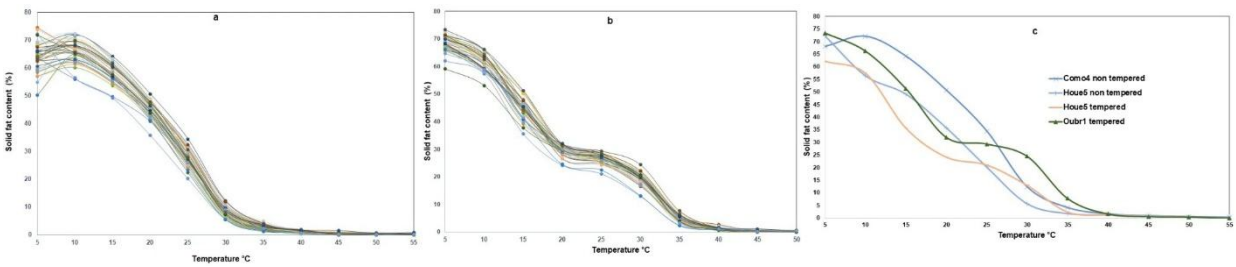

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***Figure 3**. Diversity of crystallization profiles of some crude shea butter among the 37 ones obtained by DSC based on their similarities: crystallization profiles 1 (a-b); crystallization profiles 2 (c-d); and crystallization profiles 3 (e) were identified. Typical crystallization thermal behavior was plotted in (f-h) respectively for profiles 1, 3 and 2, with the transition temperatures: c1, c2, c3 = T_{Peak}, c4 = T_{Onset}, and c' only for samples from profile 3*

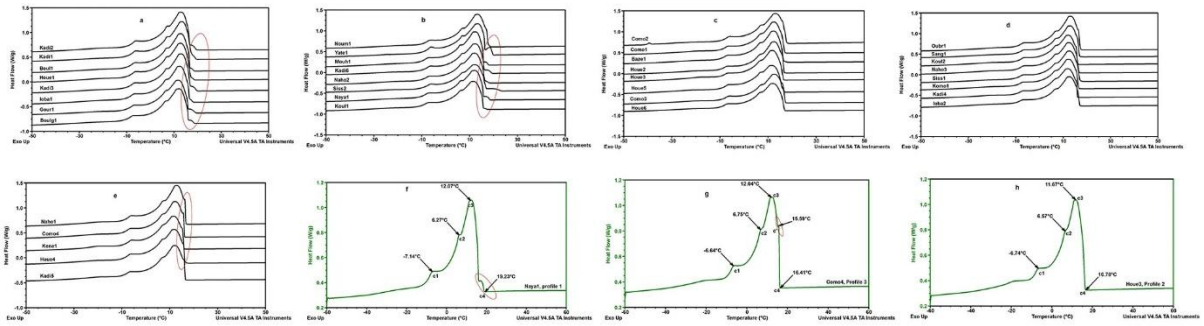

***Figure 4**. Diversity of melting profiles of some crude shea butter among the 37 ones obtained by DSC based on their enthalpy ratio ΔHf = Hf2/Hf3. Melting profiles 1, 2 and 3 were illustrated in plots (a-c), (d), and (e) respectively. Typical melting thermal behavior were plotted in (f-h) respectively for profiles 1, 2 and 3, highlighted transition temperatures (h1, h2 = T_{Onset}, h3 = T_{Peak}, and h4 = T_{End}) and the enthalpy Hf (J/g), estimated*

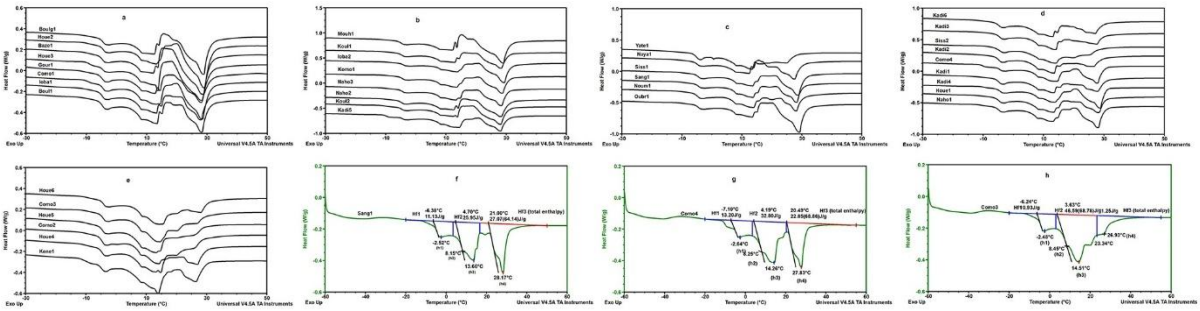

***Table 7**. Transition temperature of melting and crystallization of crude shea butter*

Sample	Melting characteristics								Crystallization characteristics				
	h2	h3	h4	Hf1	Hf2	Hf3	Total Hf	ΔHf	c1	c2	c3	c4	c'
$Baze_1$	3.5 ± 0.3	12.1 ± 0.1	28.5 ± 0.1	11.7 ± 0.3	20.0 ± 0.2	35.1 ± 0.4	66.7 ± 0.1	0.6 ± 0.1	- 6.9 ± 0.1	6.6 ± 0.1	12.2 ± 0.1	18.4 ± 0.1	-
$Boul_1$	4.0 ± 0.1	13.4 ± 0.1	28.1 ± 0.1	12.0 ± 0.3	27.5 ± 0.8	29.5 ± 0.4	69.0 ± 0.9	0.9 ± 0.1	- 6.8 ± 0.1	6.8 ± 0.1	12.7 ± 0.1	18.7 ± 0.1	-
$Boulg_1$	3.9 ± 0.1	12.4 ± 0.1	28.9 ± 0.2	11.5 ± 0.1	17.8 ± 0.7	34.9 ± 1.9	64.2 ± 1.1	0.5 ± 0.1	- 7.3 ± 0.1	6.4 ± 0.1	12.1 ± 0.6	19.3 ± 0.1	-
$Como_1$	3.9 ± 0.1	13.2 ± 0.1	28.2 ± 0.1	12.2 ± 0.1	26.4 ± 0.4	32.8 ± 1.0	71.4 ± 0.5	0.8 ± 0.1	- 6.7 ± 0.1	6.8 ± 0.1	12.3 ± 0.1	17.7 ± 0.1	-
$Como_2$	4.0 ± 0.1	14.2 ± 0.1	26.0 ± 0.1	16.3 ± 0.1	48.8 ± 0.2	11.3 ± 0.4	76.3 ± 0.6	4.3 ± 0.1	- 6.3 ± 0.1	7.1 ± 0.1	12.9 ± 0.1	18.5 ± 0.1	-

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$Como_3$	3.5 ± 0.2	14.4 ± 0.2	27.2 ± 0.3	11.4 ± 0.6	47.6 ± 1.4	11.3 ± 0.1	70.3 ± 2.1	4.2 ± 0.1	- 6.2 ± 0.1	7.1 ± 0.1	12.7 ± 0.4	17.6 ± 0.3	-
$Como_4$	4.2 ± 0.1	14.3 ± 0.1	27.8 ± 0.1	13.1 ± 0.1	31.4 ± 2.1	24.4 ± 2.1	68.8 ± 0.1	1.3 ± 0.2	- 6.7 ± 0.1	6.8 ± 0.1	12.0 ± 0.1	16.4 ± 0.1	15.6
$Gour_1$	3.1 ± 0.1	12.7 ± 0.1	27.8 ± 0.3	11.8 ± 0.5	25.4 ± 0.9	29.1 ± 1.2	66.3 ± 0.2	0.9 ± 0.1	- 7.0 ± 0.1	6.5 ± 0.1	11.5 ± 0.1	19.2 ± 0.4	-
$Houe_1$	3.1 ± 0.4	13.5 ± 0.2	28.1 ± 0.1	12.2 ± 0.2	30.4 ± 0.2	26.2 ± 0.9	68.8 ± 1.2	1.2 ± 0.1	- 6.5 ± 0.2	6.9 ± 0.1	12.4 ± 0.3	18.4 ± 1.0	-
$Houe_2$	4.2 ± 0.3	13.1 ± 0.2	28.9 ± 0.2	11.2 ± 0.1	21.2 ± 1.1	34.4 ± 1.5	66.8 ± 0.5	0.6 ± 0.1	- 7.0 ± 0.1	6.6 ± 0.1	12.1 ± 0.1	17.2 ± 0.1	-
$Houe_3$	3.2 ± 0.2	13.7 ± 0.1	28.2 ± 0.1	11.9 ± 0.1	23.5 ± 0.3	35.1 ± 0.1	70.6 ± 0.4	0.7 ± 0.1	- 6.8 ± 0.1	6.5 ± 0.1	11.6 ± 0.1	16.8 ± 0.1	-
$Houe_4$	2.9 ± 0.4	14.7 ± 0.1	27.0 ± 0.1	13.2 ± 0.1	34.2 ± 0.1	22.7 ± 0.2	70.0 ± 0.1	1.5 ± 0.1	- 6.4 ± 0.1	7.0 ± 0.1	11.7 ± 0.3	17.6 ± 0.2	15.6
$Houe_5$	2.7 ± 0.1	13.4 ± 0.2	26.0 ± 0.3	11.9 ± 1.5	35.2 ± 1.8	19.1 ± 1.5	66.2 ± 4.8	1.8 ± 0.1	- 6.6 ± 0.3	6.6 ± 0.4	11.1 ± 0.1	17.7 ± 0.2	-
$Houe_6$	3.5 ± 0.2	14.4 ± 0.1	28.1 ± 0.2	12.9 ± 1.0	43.0 ± 1.2	14.0 ± 0.7	70.0 ± 0.4	3.1 ± 0.2	- 6.8 ± 0.1	6.7 ± 0.1	11.8 ± 0.1	17.5 ± 0.3	-
$Ioba_1$	3.9 ± 0.4	13.2 ± 0.1	28.0 ± 0.2	12.3 ± 0.1	26.2 ± 0.6	28.5 ± 0.3	67.0 ± 0.3	0.9 ± 0.1	- 6.9 ± 0.1	6.5 ± 0.1	12.0 ± 0.1	18.4 ± 0.3	-
$Ioba_2$	4.6 ± 0.2	13.7 ± 0.1	29.3 ± 0.1	9.9 ± 0.3	20.1 ± 0.5	32.0 ± 1.0	62.1 ± 0.8	0.6 ± 0.1	- 7.1 ± 0.1	6.5 ± 0.1	12.0 ± 0.3	17.9 ± 0.3	-
$Kadi_1$	2.9 ± 0.2	13.4 ± 0.1	27.6 ± 0.3	12.7 ± 0.1	29.6 ± 0.2	27.3 ± 0.3	69.7 ± 0.1	1.1 ± 0.1	- 6.3 ± 0.1	7.0 ± 0.1	12.9 ± 0.1	19.6 ± 0.5	-
$Kadi_2$	3.5 ± 0.2	13.6 ± 0.1	26.4 ± 0.1	12.8 ± 0.3	32.1 ± 1.5	25.2 ± 0.5	70.1 ± 2.3	1.3 ± 0.1	- 6.4 ± 0.2	7.0 ± 0.2	12.7 ± 0.1	19.6 ± 0.3	-
$Kadi_3$	4.0 ± 0.3	14.1 ± 0.1	27.6 ± 0.1	11.7 ± 0.3	29.1 ± 1.6	25.2 ± 0.1	66.1 ± 1.4	1.2 ± 0.1	- 6.7 ± 0.1	6.7 ± 0.1	12.5 ± 0.1	20.0 ± 0.2	-
$Kadi_4$	3.8 ± 0.1	13.6 ± 0.1	28.7 ± 0.1	11.3 ± 0.1	27.1 ± 0.1	26.3 ± 0.2	64.7 ± 0.3	1.0 ± 0.1	- 6.8 ± 0.1	6.9 ± 0.1	11.9 ± 0.1	16.8 ± 0.6	-
$Kadi_5$	4.1 ± 0.1	14.3 ± 0.1	28.0 ± 0.1	13.3 ± 0.1	27.6 ± 0.4	29.4 ± 0.9	70.2 ± 1.4	0.9 ± 0.1	- 6.5 ± 0.2	6.8 ± 0.1	12.1 ± 0.2	16.8 ± 0.1	15.7
$Kadi_6$	2.6 ± 0.1	13.0 ± 0.1	27.1 ± 0.1	12.5 ± 0.1	29.1 ± 0.3	25.1 ± 0.1	66.6 ± 0.3	1.2 ± 0.1	- 6.5 ± 0.1	7.0 ± 0.1	12.2 ± 0.1	19.6 ± 0.3	-
$Kene_1$	2.2 ± 1.7	14.1 ± 0.2	26.8 ± 0.5	13.2 ± 0.6	37.8 ± 4.6	20.2 ± 0.4	71.1 ± 4.9	1.9 ± 0.3	- 6.5 ± 0.3	7.0 ± 0.3	11.2 ± 0.3	16.0 ± 0.4	15.1
$Komo_1$	4.2 ± 0.5	13.4 ± 0.1	28.6 ± 0.1	11.0 ± 0.6	25.8 ± 1.7	28.6 ± 0.1	65.4 ± 2.1	0.9 ± 0.1	- 6.8 ± 0.3	6.6 ± 0.1	11.9 ± 0.1	17.3 ± 0.4	-
$Koul_1$	3.4 ± 0.1	12.8 ± 0.1	28.0 ± 0.3	12.3 ± 0.5	23.6 ± 1.3	28.7 ± 0.1	64.5 ± 1.8	0.8 ± 0.1	- 7.2 ± 0.3	6.2 ± 0.3	11.6 ± 0.2	17.7 ± 0.2	-
$Koul_2$	3.2 ± 0.1	13.7 ± 0.1	28.1 ± 0.1	12.2 ± 0.1	22.9 ± 0.5	32.2 ± 0.7	67.3 ± 1.2	0.7 ± 0.1	- 6.5 ± 0.1	6.8 ± 0.1	11.8 ± 0.1	16.9 ± 0.1	-
$Mouh_1$	3.1 ± 0.2	12.2 ± 0.1	29.0 ± 0.1	11.8 ± 0.6	20.1 ± 0.4	35.7 ± 1.5	67.6 ± 2.4	0.6 ± 0.1	- 7.5 ± 0.2	6.1 ± 0.1	12.2 ± 0.1	18.8 ± 0.9	-
$Naho_1$	3.7 ± 0.2	13.0 ± 0.1	28.0 ± 0.1	11.9 ± 0.3	29.7 ± 0.5	29.4 ± 0.5	71.0 ± 0.3	1.0 ± 0.1	- 6.4 ± 0.1	7.1 ± 0.1	12.8 ± 0.1	17.9 ± 0.1	16.3
$Naho_2$	3.3 ± 0.1	12.5 ± 0.1	28.2 ± 0.2	11.7 ± 0.2	23.6 ± 0.1	32.0 ± 0.7	67.3 ± 0.8	0.7 ± 0.1	- 6.8 ± 0.2	6.5 ± 0.1	12.0 ± 0.1	18.6 ± 0.1	-
$Naho_3$	4.5 ± 0.1	13.3 ± 0.1	28.3 ± 0.1	11.5 ± 0.3	26.2 ± 0.7	28.1 ± 0.4	66.2 ± 0.6	0.9 ± 0.1	- 6.7 ± 0.1	6.7 ± 0.1	12.3 ± 0.1	17.3 ± 0.1	-
$Naya_1$	2.9 ± 0.1	12.4 ± 0.1	27.6 ± 0.1	11.6 ± 0.1	23.0 ± 0.4	31.2 ± 1.5	65.7 ± 1.2	0.7 ± 0.1	- 7.3 ± 0.2	6.3 ± 0.1	11.9 ± 0.2	18.9 ± 0.4	-
$Noum_1$	4.0 ± 0.1	13.8 ± 0.1	28.1 ± 0.1	12.9 ± 0.1	28.8 ± 0.1	30.5 ± 0.1	72.2 ± 0.1	0.9 ± 0.1	- 6.6 ± 0.1	7.0 ± 0.1	13.0 ± 0.2	19.4 ± 0.2	-

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$Oubr_1$	4.3 ± 0.3	13.3 ± 0.1	29.1 ± 0.1	11.8 ± 0.1	23.7 ± 1.5	36.0 ± 0.1	71.5 ± 1.5	0.7 ± 0.1	- 6.5 ± 0.1	6.9 ± 0.1	13.0 ± 0.1	18.2 ± 0.1	-
$Sang_1$	4.6 ± 0.1	13.7 ± 0.1	28.3 ± 0.1	11.0 ± 0.2	25.6 ± 0.5	27.1 ± 0.1	63.7 ± 0.7	1.0 ± 0.1	- 6.8 ± 0.4	6.7 ± 0.2	12.3 ± 0.5	18.2 ± 0.1	-
$Siss_1$	4.1 ± 0.7	13.4 ± 0.2	28.6 ± 0.1	11.8 ± 0.1	24.2 ± 1.4	30.3 ± 0.4	66.3 ± 1.1	0.8 ± 0.1	- 6.8 ± 0.2	6.7 ± 0.1	12.2 ± 0.2	18.3 ± 0.2	-
$Siss_2$	2.3 ± 0.2	14.1 ± 0.1	25.4 ± 0.2	9.7 ± 0.4	32.1 ± 1.5	21.8 ± 0.6	63.6 ± 1.6	1.5 ± 0.1	- 6.4 ± 0.1	6.9 ± 0.2	11.8 ± 0.1	22.4 ± 1.3	-
$Yate_1$	- 3.8 ± 0.1	13.4 ± 0.1	25.0 ± 0.1	15.6 ± 0.9	27.7 ± 0.1	29.3 ± 0.2	72.5 ± 0.7	1.0 ± 0.1	- 6.0 ± 0.1	7.0 ± 0.1	12.9 ± 0.2	20.2 ± 0.2	-

Analyses were done in triplicate per sample and values were recorded as the mean ± SD

Multivariate Analysis

The influence of the investigated quality parameters on the thermal behavior of crude SB was assessed using the Pearson correlation test at α = 0.05, and principal component analysis (PCA). PCA aimed to determine variables that significantly impact the selected principal components (PC), extracting and storing the most important data. Only variables that significantly impact the PC were selected (37 individuals and 21 variables, as shown in Figure 5a and b) for PCA and clusters analysis (CA). Samples clustering involved classifying them based on individual similarity index (Gower distance). The analysis of the PCA plots is shown in Figure 5.

Firstly, Pearson correlation test was performed to establish relationship between chemical parameters and thermal behavior determined by DSC and SFC. A Pearson correlation coefficient *(R)* value of at least 0.50 indicated a statistically significant positive or negative relationship, whereas values below 0.50 indicated no significant correlation. On the one hand, the statistically significant relationship between SFC and chemicals parameters showed moderate negative (*R* = -0.70, *p-value* = 1.66E-06) and positive (*R* = 0.50, significant *p-value*) correlations for the FFA-SFC non-tempered method at 35 °C and the UMC-SFC tempered method at 35 °C, respectively. On the other hand, Table 8 showed the correlation coefficients between the chemical parameters and thermal behavior by DSC according to their profiles. The results indicate that thermal behavior of crude SB, may depend on chemical quality, such as FA content and chemical indexes.

The parameters that exhibited the greatest influence were UMC and FFA, sorted with the strongest. Correlations between UMC-c' and UMC-c3 were 0.98 and 0.96, respectively. For FFA-h4, the correlation was *R*= -0.88 at *p-value* = 5.19E-08. The FA content also showed significant correlations with c4, *R* = 0.77 for C16:0-c4, *R* = -0.72 for C18:1-c4, and *R* = 0.71 for C18:0-c4 (see Table 8).

Figure 5a) present a graphical arrangement of the investigated variables and illustrates the correlations between them. The analysis of the graphs does not detect any outliers. The main factors accounted for 64.51% of the variation (PC1: 31.05, PC2: 21.71% and ¨PC3: 11.75%). This result means that 64.51% of the variability is explained by the plane. The PCA results confirmed the strongest significant positive correlation between chemical and thermal parameters as follows: FFA-c1, FFA-ΔH_f, UMC-h4, UMC-c3, UMC-c4, UMC-c' and C16:0-c4; as well as C18:0-c4. Additionally, the strongest significant negative correlation, as shown in the PCA and in agreement with Pearson results, include

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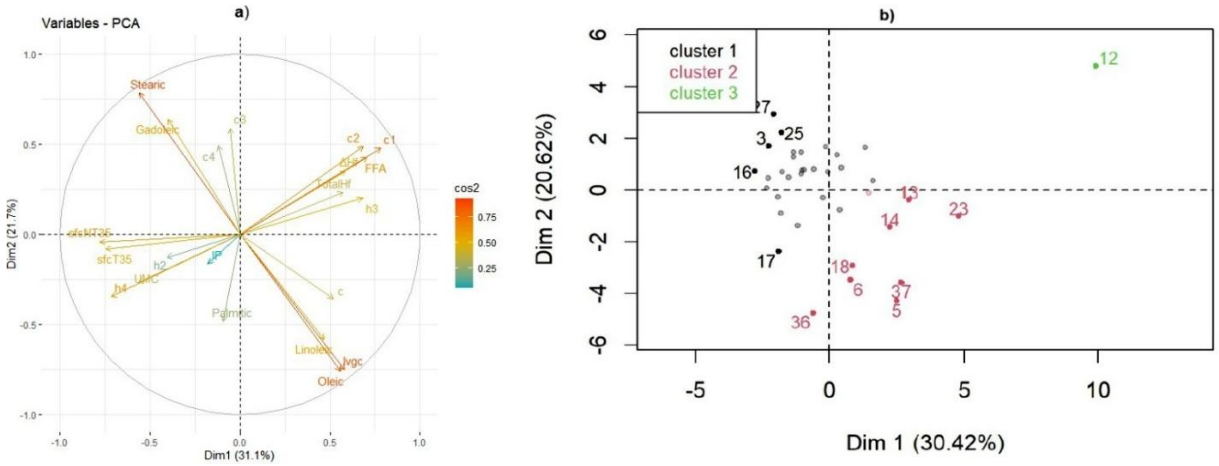
Status : Postprint (Author's version)

correlations between FFA-h4, FFA-c', UMC-c4, and correlation between C18:1-c4. PC1-PC2 were mostly explained by the variables with the strongest contributions (C18:0, C18:1, C18:2, C20:1, IV_{GC}, FFA, c1, ΔHf, SFCNT35, SFCT35 and h4), with both negative and positive coordinate on the plane. However, the residual variance of PC3 accounted for 11.75%, was mostly explained by Total Hf, c2, c3, c4, h2, UMC and C16:0, also with negative and positive coordinate on the plane.

Hierarchical ascending classification of the individuals, shown in Figure 5b), reveals 3 clusters formed from individuals with the highest contribution to the plane construction. The number of clusters were performed independently, using R Software. The first cluster (cluster 1) includes individuals such as $Boulg_1$ (corresponding to number 3 in the graph), $Ioba_2$ (number 16), $Kadi_1$ (number 17), $Koul_1$ (number 25) and $Mouh_1$ (number 27). This cluster is characterized, on the one hand, by high values for SFC at 35 °C using non-tempered method (SFCNT35), h4, SFC at 35 °C using tempered method (SFCT35), UMC and h2. On the other hand, samples in cluster 1 were characterized by low values for FFA, ΔHf, h3, c1, c2 and Total Hf. Cluster 2 consist of individuals such as $Como_2$ (5), $Como_3$ (6), $Houe_5$ (13), $Houe_6$ (14), $Kadi_2$ (18), $Kene_1$ (23), $Siss_2$ (36) and $Yate_1$ (37). Samples in the later clusters were characterized, on the one hand, by high values for FFA, ΔHf, c1, h3, c2 and Total Hf, and in the other hand by low values for SFCNT35, h4, SFCT35, UMC and h2. Finally, the cluster 3 consist of only $Houe_4$ (12), an extreme individual, characterized by high values for IV_{GC}, C18:2, C18:1, c' and C16:0. Sample $Houe_4$ is also characterized by low values for C18:0 and C20:1.

Figure 5*. (a) Loading and score plots of PC1-PC2, "Variables-PCA". (b) Ascending hierarchical classification "Individuals-PCA" of the individual analysis of crude shea butter from Burkina Faso. The labelled individuals are those with the higher contribution to the plane construction. Results were recorded according to chemical selected parameters and thermal parameters. SFCNT35 = SFC at 35°C for non-tempered method; SFCT35 = SFC at 35°C for tempered method. Numbers correspond to samples sorted alphabetically, as shown in the Table 2. c1, c2, c3, c4 and c' are the transition temperatures*



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Status : Postprint (Author's version)

***Table 8**. Correlation coefficient between chemical and DSC thermal behavior parameters of crude shea butter*

Parameters		Correlation coefficient *(R)*	*p*-value *
Chemical	Thermal		
A) Correlation established for crystallization profile A			
FFA	c1	0.82	8.404e-05
C16:0	c3	-0.59	0.015
C20:1	c3	0.69	0.003
FFA	c4	0.62	0.011
IV_{GC}	c4	-0.68	0.004
UMC	c4	-0.75	0.000
C18:0	c4	0.71	0.002
C18:1	c4	-0.72	0.001
B) Correlation established for crystallization profile B			
IV_{GC}	c3	-0.56	0.023
C18:0	c3	0.59	0.015
C18:1	c3	-0.50	0.048
C) Correlation established for crystallization profile C			
FFA	c3	-0.68	0.21
UMC	c3	0.96	0.009
FFA	c4	-0.59	0.290
UMC	c4	0.80	0.100
C16:0	c4	0.77	0.130
C18:2	c4	0.55	0.340
FFA	c'	-0.71	0.180
UMC	c'	0.98	0.003
D) Correlation established for melting profile A			
FFA	h4	-0.88	5.19E-08
C16:0	h4	-0.54	0.010
C16:0	c4	0.55	0.008
FFA	ΔHf	0.53	0.011
E) Correlation established for melting profile B			
UMC	h3	-0.50	0.170
UMC	h4	0.73	0.027
FFA	ΔHf	0.80	0.010
F) Correlation established for melting profile C			
C20:1	h3	0.58	0.220
C16:0	h3	0.60	0.210

* $p < 0.05$ (significant) and $p > 0.05$ (non-significant)

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Conclusions

Various processes exist in Burkina Faso to extract crude shea butter involving, traditional and semi-mechanized methods. The butters collected from various regions in Burkina Faso were characterized by a relatively high content of unsaponifiable matter, C18:0 and C18:1. However, the most significant differences were found in the physical and chemical characteristics among the 37 samples. A great diversity was found in the thermal properties (crystallization and melting behavior and solid fat content), allowing for classification based on their profiles. Statistically significant relationships were established between the investigated chemical parameters (FFA, IV, UMC, FA) and thermal properties, as confirmed by PCA and Pearson test. Furthermore, clustering analysis was performed to classify samples based on their characteristics. The results highlighted the great diversity of crude shea butter from Burkina Faso, extracted by various non-standardized processes. The non-standardization of extraction processes leads to the diversity found in chemical quality. Implementing standardized processes could enhance the quality and commercial viability of shea butter products.

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AUTHOR CONTRIBUTIONS

"Bertrand W. F. Goumbri conceived and designed the study and collected the data. Bertrand W. F. Goumbri wrote the first draft of the manuscript. Bertrand Goumbri and Alfred Kouassi analyzed the data. Sabine Danthine proofread the manuscript. Sabine Danthine, Roland Marini Djang'eing'a, Touridomon Issa Somé, Rasmané Semdé and Ange Mouithys-Mickalad supervised the study. Abdoul Karim Sakira and Gérard B. Josias Yaméogo analyzed the chromatography data. Alfred Kouakou Kouassi proofread the revised manuscript. All authors contributed to approve the final draft of the manuscript."

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