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Article

Assessment of the Impact of Annual Growing Conditions on the Physicochemical Properties of Mango Kernel Fat

Alfred Kouakou Kouassi [1,*], Taofic Alabi [2,3], Giorgia Purcaro [4], Christophe Blecker [1] and Sabine Danthine [1,*]

1 Food Science and Formulation, University of Liège-Gembloux Agro-Bio Tech, 5030 Gembloux, Belgium; christophe.blecker@uliege.be
2 Department of Animal Biology, University Peleforo Gon Coulybaly, Korhogo 1328, Côte d'Ivoire; atafci@gmail.com
3 Functional and Evolutionary Entomology, University of Liège-Gembloux Agro-Bio Tech, 5030 Gembloux, Belgium
4 Analytical Chemistry, University of Liège-Gembloux Agro-Bio Tech, 5030 Gembloux, Belgium; gpurcaro@uliege.be
* Correspondence: akouassi@uliege.be (A.K.K.); sabine.danthine@uliege.be (S.D.)

Abstract: In this study, the effect of growing conditions in different harvest years on the physicochemical properties of various Ivorian mango kernel fat (MKF) varieties was investigated. The fats extracted from mango kernels were analysed with respect to their fatty acid composition (FAC) and triacylglycerol (TAG) composition, melting profile, and solid fat content (SFC). The results indicate that variations in MKF content between non-consecutive harvest years (2021 and 2023) were influenced by environmental conditions, particularly rainfall and genetic factors, demonstrating the diverse response to environmental changes. Traditional varieties showed a decrease in fat content in the drier year (2023), while commercial varieties exhibited an increase. FAC was also affected, with changes in oleic- and stearic-acid levels, depending on water availability. This impacted the TAG composition, which in turn influenced the physical characteristics of the MKF. These findings highlight the importance of climatic factors in determining the quality and characteristics of MKF, which have significant implications for industrial applications. This suggests that it is necessary to take into account such factors when implementing logistic chains for the supply of quality raw materials.

Keywords: climate change; mango variety; Côte d'Ivoire; mango kernel fat; composition; physicochemical characteristics; year-to-year variation; harvest

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1. Introduction

The continuing growth of the global population has necessitated the development of new food sources to meet basic human needs. The increase in demand for edible fats and oils has resulted in the toxicological, nutritional, and technological evaluation of oils from unconventional sources and those traditionally considered agricultural by-products.

Mango seed is among these by-products and is an interesting source of fat (4–15%), rich in stearic (St) and oleic (O) acid with three major triacylglycerols (StOSt, StOO, and StLSt, with L = linolenic acid) [1,2].

Mango (*Mangifera indica* L.) belongs to the Anacardiaceae family. Indigenous to the Indian subcontinent, it is an important fruit crop cultivated in tropical and subtropical regions. This perennial crop grows in semi-arid, frost-free conditions, with a distinct alternation between dry and wet seasons [3]. The mango growing cycle can be divided into four main phenological phases: vegetative growth, dormancy, flowering, and fruiting [4]. A dry season lasting two to three months induces vegetative dormancy and promotes flowering. To flower, the mango tree requires a complete cessation of vegetative growth, induced by a drop in average temperatures and/or by a pronounced dry period. Thus, the phenological cycle of the mango tree is highly influenced by climatic conditions [4,5].

Some studies have also shown that factors inherent to the plant influence the phenological cycle [6,7]. Mango fruit is a drupe, and the flattened kernel is protected by a lignified tegument: the seed.

Mango seed kernel (MSK) is a potential source of fat, protein, carbohydrate, starch, and bioactive compounds. These macro- and micro-nutrients have huge potential in food and processing industries. MSK is used as a substitute for wheat flour in the manufacture of antioxidant-rich biscuits [8,9]. MSK starch has been used as an edible coating to extend the shelf-life of tomatoes. Likewise, Melo et al. [10] developed an antioxidant film using MSK starch and MSK phenolic extract. Mango kernel fat (MKF), one of the main potential value-added products of MSK, possesses significant functional and physicochemical characteristics that make it a suitable substitute for other fats in the food, pharmaceutical, and cosmetic industries. It is one of the six vegetable fats permitted for use in the production of cocoa butter equivalents (CBE), according to European Union Directive 2000/36/EC [11]. MKF has particularly been used to improve the hardness of dark chocolate [12]. Similarly, the addition of MKF in the preparation of muffins improved the tenderness, colour, and phenolic content [13]. MKF is also widely used in the industry for the manufacture of soap, shampoos, and body lotions [14,15].

Mango is a widely cultivated fruit in Côte d'Ivoire, with an annual production of 180,000 tons [16]. The main cultivation areas are concentrated in the northern part of the country. About 30 varieties grow in the country, including both traditional and grafted cultivars. However, a large number of seeds, the main by-product resulting from mango processing and consumption, remain underutilized.

Mango seed has received increased attention in the vegetable fat industry for the reasons mentioned above, as well as the interesting properties of its fat for food and non-food use. In order to valorise this by-product, we have recently explored the potential of various MKFs from the Côte d'Ivoire through extraction and physicochemical characterization [2,17]. However, MKF yield and chemical composition, upon which the fat's suitability for nutrition, food, pharmaceutical, and cosmetic applications are dependent, could be affected by climate conditions.

Climate change is having a major impact on agriculture, affecting crop production, product composition, and overall food security. Various regions, including West Africa and particularly the Côte d'Ivoire, have experienced higher temperatures, more erratic rainfall patterns, and more frequent droughts as a result of these global changes.

Considering the ongoing climatological situations, it is essential to evaluate how different mango tree cultivars perform under diverse climate conditions. Therefore, this study aims to assess the occurrence or non-occurrence of variability in the physicochemical properties of various Ivorian MKF varieties depending on the harvesting year.

2. Materials and Methods

2.1. Harvest and Extraction

The Ripe Mango (reached maturity) of four varieties—two grafted or commercial varieties, Kent (KT) and Amelie (AM), and two local varieties, Dadiani (DI) and Djakoumankoun (DN)—were collected in Korhogo province, Côte d'Ivoire, and hand-peeled to extract the seeds. The recovered seeds were immediately heat-treated (cooked at 98 $\pm$ 2 °C for 15 min at atmospheric pressure) to inactivate lipases, followed by sun-drying for 2 days. Subsequently, the mango seeds were manually shelled to extract the kernels, which were then sun-dried for an additional 2 weeks. The samples were then transferred to the Food Science and Formulation Laboratory (TERRA, Uliege GxABT, Gembloux, Belgium), where they were ground into a powder with a particle size of 1 mm using a high-speed lab mill (FRITSCH, 19.1020/00426, ROHS, Idar-Oberstein, Rhénanie-Palatinat, Germany). The powder was stored in a sealed plastic container under vacuum at 4 °C until use. The experiments were conducted over 2 non-consecutive years, during the 2021 and 2023 mango maturity seasons between April and May.

Fat extraction was carried out using the maceration method as described by Kouassi et al. [2]. 200 mL of hexane was added to 100 g of the sample, and the mixture was heated to 40 °C with stirring for 90 min. The extracts were then centrifuged at 7000× *g* rpm at 30 °C for 15 min using a Jouan C312 centrifuge (France) and, finally, filtered through Whatman No. 1 filter paper (Ø125 mm). The extraction process was repeated 3 times, and the collected filtrates were combined in a flask. Subsequently, the solvent was removed using a rotary evaporator (Büchi Labortechnik AG, Flawil, Switzerland), and any residual solvent traces were further eliminated by nitrogen flushing. The extracted fats were further stored in the dark at −20 °C until analyses. All fats were extracted in triplicate.

2.2. Fatty Acid Composition by Gas Chromatography

Fatty acid composition determination was carried out using a Trace GC Ultra gas chromatograph (GC Thermo Fisher Scientific, Zaventem, Belgium) fitted with a flame ionization detector (FID), as described by Fina et al. [18]. The fatty acid methyl esters were prepared using a one-step microwave-assisted extraction technique and were analysed in GC–FID using a Stabliwax DA column (Restek Corporation, Bellefonte, PA, USA) of 30 m × 0.25 µm × 0.25 µm (length × thickness × diameter). The injection was performed in splitless mode (splitless time: 0.85 min) at 250 °C. Helium was used as the carrier gas with a flow rate of 1 mL/min in constant flow. The temperature program was set as follows: 50 °C (hold of 1 min) to 150 °C at 30 °C/min and to 240 °C (hold for 10 min) at 5 °C/min. FID was set at 250 °C. The fatty acid methyl esters were identified by comparing their retention times with those of the pure reference. All the measurements were carried out in triplicate.

2.3. Triacylglycerol Composition

Triacylglycerol (TAG) analysis was carried out with an HPLC SHIMADZU (Shimadzu Corporation, L21466112486, Kyoto, Japan) system equipped with a refractive index detector (RID-20A) and two stainless steel Nova-Pak C18 columns (4 µm, 3.9 × 150 mm; Waters, Belgium) according to a modified method of Danthine et al.'s [19] for oil TAG analysis, both set at a temperature of 30 °C. The mobile phase was a mixture of acetone/acetonitrile 60/40 *v*/*v* with a flow rate of 1.2 mL/min; injection volume 20 µL. TAGs were identified using their equivalent carbon numbers and by comparing with mango kernel fat of known TAG composition. The content of each TAG was expressed as a relative percentage. All the measurements were performed in triplicate.

2.4. Melting Profiles by p-NMR

The melting behaviour of each extracted MKF was examined using p-NMR between 5 °C and 40 °C, using a Minispec-mq20 spectrometer (Bruker, Karlsruhe, Germany) according to the IUPAC method 2.150a (ex 2.323) [20]. The non-tempered serial method for routine use was applied. Data are expressed as the average of three independent measurements.

2.5. Melting Profiles by Differential Scanning Calorimetry (DSC)

DSC melting profiles were determined using aluminium T0 hermetic pans following the method described by Danthine [21] using a Q2000 DSC equipped with a refrigerated cooling system (TA Instruments, New Castle, DE, USA). Fat samples of 2–4 mg were placed in T0 hermetic pans; an empty pan of the same type was used as a reference. The time–temperature program was set as follows: Samples were first heated to 80 °C to ensure complete melting and held at this temperature for 10 min. They were then cooled to −60 °C at a rate of −10 °C/min and held at −60 °C for 30 min before being reheated at a rate of 5 °C/min to record the melting profiles from −60 °C to 80 °C. Universal Analysis Software version 4.2 (TA Instruments, New Castle, DE, USA) was employed for peak temperature measurements. All the measurements were carried out in triplicate.

2.6. Statistical Analysis

Minitab 21 software (Minitab Inc., Coventry, UK) was utilized for performing one-way ANOVA and Tukey's tests to determine significant differences, with a *p*-value threshold of $p < 0.05$.

3. Results

3.1. Weather Conditions and Plant Phenology

The climate of the region is typical of the northern area of Côte d'Ivoire (Sudanese type) and is characterized by a single rainy season lasting six and a half months (mid-April to October), with a peak from July to October, and a dry season with maximum intensity from November to the end of March. The average annual rainfall is around 1200 mm, with temperature variations between 25 °C and 30 °C in the region.

Temperature and rainfall patterns in the Korhogo area during the two harvest years (2021 and 2023) are shown in Figure 1. The distribution of rainfall varied between different years and phenological stages of the mango tree. Three important phenological stages of the mango tree, flowering, vegetative growth, and maturation, occur between January and May. In the first year (2021), precipitation in this period reached a total of 137.4 mm, while in the second year (2023), the trees received 213 mm of rain (Figure 1). The rainfall patterns were different in the two harvest years. Temperatures during this period were almost the same in both years (Figure 1). The highest temperatures were recorded in March, at 30.7 °C and 30.8 °C for 2021 and 2023, respectively.

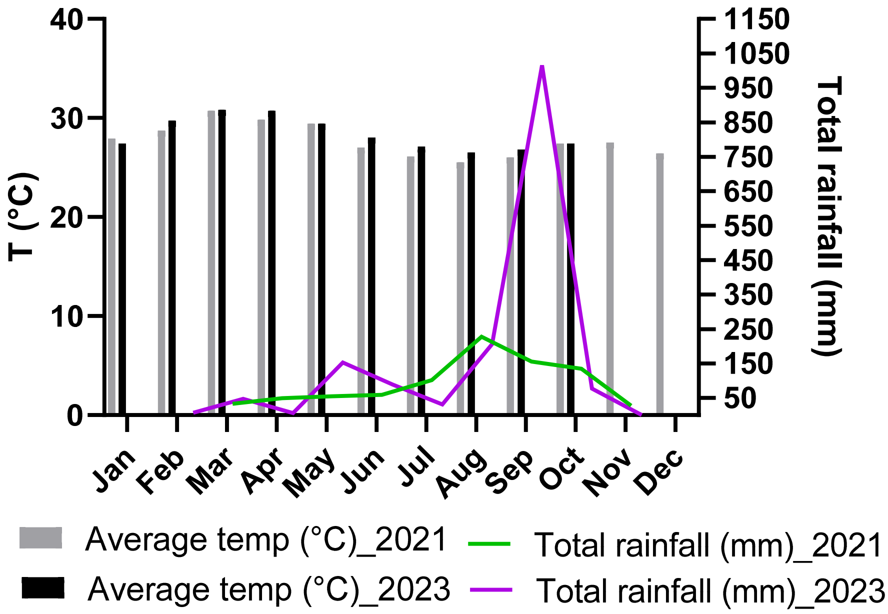

Figure 1. Meteorological data of monthly rainfall and average temperatures collected at the M–TAR/SYNOP station for the years 2021 and 2023.

3.2. Fat Content

The content of the extracted MKF is presented in Figure 2. A significant difference ($p < 0.05$) was found between the samples harvested during the two years. A drop in the fat content of DN (9.57 g/100 g ± 0.01 → 9.45 g/100 g ± 0.02) and DI (9.37 g/100 g ± 0.02 → 8.38 g/100 g ± 0.03) was observed in 2023, while an increase in content was found for KT (7.57 g/100 g ± 0.06 → 8.52 g/100 g ± 0.01) and AM (4.89 g/100 g ± 0.05 → 5.31 g/ 100 g ± 0.07). Despite this change, as expected, the MKF content largely depended on the mango variety. We noticed a change in the ranking of the samples with respect to fat content between the two harvesting years. In the first year (2021), DN had the highest fat content, followed by DI, and then KT and AM. In contrast, in 2023, the fat content of sample KT was higher than that of sample DI.

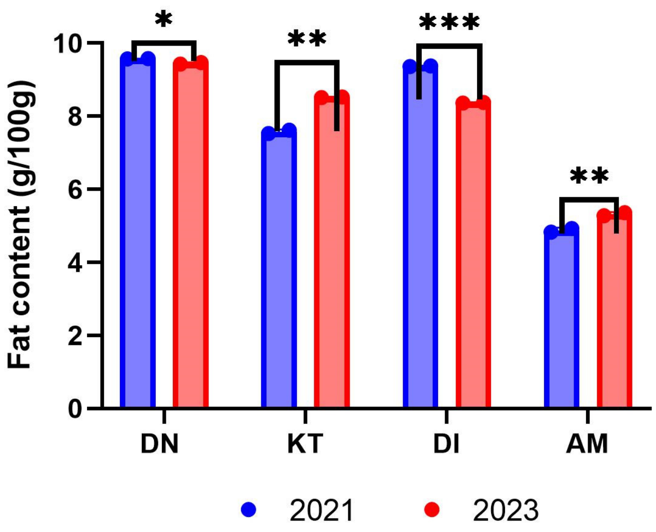

Figure 2. Effects of 2021 and 2023 harvest years on fat content in cvs. Dadiani (DI), Kent (KT), Djakoumankoun (DN), and Amelie (AM) mango kernel fats between 2021 and 2023. * indicates a statistically significant difference. Here, the more stars there are, the greater the difference.

3.3. Fatty Acid Composition

The fatty acid composition of various MKFs is shown in Table 1. The most abundant fatty acids were stearic acid (St, 30–49%) and oleic acid (O, 35–48%), followed by palmitic (*p*, 7–14%) and linoleic acid (L, 4–10%). On the other hand, arachidic acid (A, 1–3%) and linolenic acid (0.3–1.2%) were present in the lowest quantities. Regardless of the harvesting year, oleic acid and stearic acid were the major fatty acids in all the samples. Significant variations ($p < 0.05$) were observed in the proportion of the predominant fatty acids within the same varieties during the two harvest years. Specifically, all mango tree varieties exhibited a decrease in the proportion of palmitic acid and linoleic acid in the second year of harvest. The trend (increasing/decreasing) was different for the other main fatty acids. The proportion of oleic acid increased relatively for DN (38.9 → 43.9%), DI (41.4 → 43.3%), and AM (43.9 → 44.3%), while it decreased for KT (47 → 46.95%). In contrast, KT exhibited an increase in stearic acid content (35 → 37.6%), whereas DN (48.3 → 46.2%) and DI (40.6 → 40.4%) showed a relative decrease in 2023. Despite the increase in the oleic acid content of AM, there was also an increase in the amount of stearic acid in 2023 (30.3 → 31.8%).

Table 1. Effects of 2021 and 2023 harvest years on the levels of different fatty acids (%) in cvs. Dadiani, Kent, Djakoumankoun, and Amelie mango kernel fats between 2021 and 2023.

Variety	Dadiani (DI)		Kent (KT)		Djakoumankoun (DN)		Amelie (AM)	
FA (%)	2021	2023	2021	2023	2021	2023	2021	2023
Palmitic acid (*p*)	9.50 [c] ± 0.02	8.59 [e] ± 0.03	9.39 [d] ± 0.04	7.72 [g] ± 0.05	8.28 [f] ± 0.12	7.28 [h] ± 0.01	13.44 [a] ± 0.9	12.10 [b] ± 0.16
Stearic acid (St)	40.62 [c] ± 0.08	40.36 [d] ± 0.05	35.07 [f] ± 0.01	37.64 [e] ± 0.14	48.33 [a] ± 0.02	46.18 [b] ± 0.12	30.26 [h] ± 2.27	31.76 [g] ± 0.06
Oleic acid (O)	41.44 [f] ± 0.01	43.29 [e] ± 0.12	47.00 [a] ± 0.03	46.95 [b] ± 0.12	35.92 [h] ± 0.09	38.94 [g] ± 0.08	43.93 [d] ± 0.66	44.25 [c] ± 0.15
Linoleic acid (L)	6.39 [c] ± 0.02	5.43 [e] ± 0.02	6.23 [d] ± 0.03	5.20 [f] ± 0.04	4.88 [g] ± 0.02	4.75 [h] ± 0.02	9.58 [a] ± 1.91	8.79 [b] ± 0.16
Linolenic (Ln)	0.32 [g] ± 0.02	0.44 [f] ± 0.01	0.49 [d] ± 0.07	0.52 [c] ± 0.01	0.31 [h] ± 0.02	0.45 [e] ± 0.01	1.11 [a] ± 0.36	1.10 [b] ± 0.01
Arachidic acid (A)	1.72 [g] ± 0.05	1.91 [e] ± 0.01	1.82 [f] ± 0.08	1.99 [d] ± 0.01	2.29 [b] ± 0.02	2.42 [a] ± 0.01	1.67 [h] ± 0.23	2.02 [c] ± 0.08

Note: Significant differences of means ($p \leq 0.05$) within a row are indicated by different letters.

3.4. Triacylglycerol Composition (TAG)

The triacylglycerol profile of MKF from the four varieties studied is presented in Table 2. Whatever the harvesting year and the variety, the main TAGs found in all MKFs were StOSt (21–47%), StOO (15–27%), and StLSt (11–15%). An appreciable amount of OOO (2–8%), POO (2–8%), StLO (2–5%), POS (2–5%), POP (1–4%), and StOA (1–5%) were also present in all MKFs. There were differences in the amount of the main TAG within the same variety between the harvest years. A relative decrease in StLSt content was observed, while StOO content was relatively increased in all the samples during the second harvest year. However, a significant change ($p < 0.05$) was only observed in StOO content for DN (15.2 to 18.2%). The trend was different for StOSt content. KT exhibited an increase in StOSt (28.3 → 28.58%) content with no significant difference, while this TAG content relatively decreased in the others, showing significant variations ($p < 0.05$) for DN and AM. Variations with different trends (steady/decreasing/increasing) were also observed in some significant triacylglycerols. However, except for DN, the amount of the total mono-, di-, and tri-unsaturated TAGs (SUS, SUU, and UUU, respectively, with S, saturated acid and U, unsaturated acid) were steady (no significant difference, $p < 0.05$) for all samples studied. In DN, the SUS content decreased (73 to 67.9%), while the SUU and UUU content increased (24.4 to 27.9% and 3.2 to 4.6%, respectively).

Table 2. Effects of 2021 and 2023 harvest years on the levels of different triacylglycerols (%) in cvs. Dadiani (DI), Kent (KT), Djakoumankoun (DN), and Amelie (AM) mango kernel fats between 2021 and 2023.

	DN		**KT**		**DI**		**AM**	
Triacylglycerol (TAG) %	**2021**	**2023**	**2021**	**2023**	**2021**	**2023**	**2021**	**2023**
LLL	0.01 ^{c} ± 00	0.08 ^{bc} ± 0.04	0.08 ^{bc} ± 0.01	0.21 ^{ab} ± 0.01	0.12 ^{bc} ± 0.03	0.10 ^{bc} ± 0.01	0.22 ^{ab} ± 0.03	0.35 ^{a} ± 0.01
OLLn	0.03 ^{c} ± 00	0.13 ^{abc} ± 0.02	0.11 ^{abc} ± 0.01	0.24 ^{abc} ± 0.03	0.14 ^{abc} ± 0.09	0.06 ^{bc} ± 0.02	0.27 ^{a} ± 0.01	0.26 ^{ab} ± 0.09
PLLn	0.03 ^{b} ± 00	0.13 ^{b} ± 0.1	0.07 ^{b} ± 0.01	0.65 ^{a} ± 0.04	0.08 ^{b} ± 0.07	0.09 ^{b} ± 0.01	0.22 ^{b} ± 0.01	0.23 ^{b} ± 0.16
OLL	0.16 ^{c} ± 0.01	0.24 ^{c} ± 0.01	0.54 ^{abc} ± 24	0.50 ^{abc} ± 0.04	0.44 ^{abc} ± 0.04	0.42 ^{bc} ± 0.07	0.90 ^{ab} ± 0.01	0.97 ^{a} ± 0.29
PLL	0.01 ^{b} ± 0.01	0.07 ^{b} ± 0.01	0.15 ^{a} ± 0.16	0.18 ^{a} ± 0.03	0.08 ^{b} ± 0.05	0.10 ^{b} ± 0.01	0.35 ^{a} ± 0.02	0.36 ^{a} ± 0.01
POLn	0.09 ^{a} ± 0.06	0.19 ^{a} ± 0.03	0.33 ^{a} ± 0.21	0.46 ^{a} ± 0.02	0.21 ^{a} ± 0.16	0.30 ^{a} ± 0.01	0.91 ^{a} ± 0.03	0.83 ^{a} ± 0.09
PLnP	0.02 ^{c} ±0.01	0.04 ^{c} ± 0.01	0.02 ^{c} ± 0.01	0.14 ^{b} ± 0.05	0.01 ^{c} ± 0.01	0.03 ^{c} ± 0.01	0.08 ^{bc} ± 0.01	0.30 ^{a} ± 0.01
OOL	0.85 ^{d} ± 0.04	1.01 ^{cd} ± 0.02	2.21 ^{b} ± 0.02	1.97 ^{b} ± 0.05	1.70 ^{b} ± 0.10	1.66 ^{bc} ± 0.17	3.15 ^{a} ± 0.13	3.07 ^{a} ± 0.41
StLL + POL	1.24 ^{b} ± 0.01	1.22 ^{b} ± 0.01	1.90 ^{b} ± 0.03	1.77^{b} ± 0.04	1.84 ^{b} ± 0.16	1.62 ^{b} ± 0.24	3.57 ^{a} ± 0.08	3.54 ^{a} ± 0.55
PLP	0.44 ^{b} ± 0.02	0.47 ^{b} ± 0.01	0.38 ^{b} ± 0.01	0.44 ^{b} ± 0.01	0.37 ^{b} ± 0.08	0.32 ^{b} ± 0.13	1.03 ^{a} ± 0.02	1.20 ^{a} ± 020
OOO	2.29 ^{d} ± 0.02	3.20 ^{c} ± 0.01	8.06 ^{a} ± 0.05	7.76 ^{a} ± 0.09	4.66 ^{b} ± 0.09	4.67 ^{b} ± 0.30	7.99 ^{a} ± 0.12	7.67 ^{a} ± 0.23
StLO	2.91 ^{e} ± 0.06	3.32 ^{de} ± 0.03	3.77 ^{cd} ± 0.04	3.71 ^{cd} ±0.06	4.67 ^{a} ± 0.05	4.38 ^{ab} ± 0.29	4.05^{bc} ± 0.26	4.21 ^{abc} ± 0.10
OOP	2.16 ^{e} ± 0.03	2.28 ^{e} ± 0.02	6.08 ^{b} ± 0.03	5.15 ^{c} ± 0.01	4.16 ^{d} ± 0.02	3.91 ^{d} ± 0.37	7.31 ^{a} ± 0.29	7.60 ^{a} ± 0.30
StLP	1.97 ^{bc} ± 0.07	2.05 ^{bc} ± 0.02	1.61 ^{c} ±0.02	1.56 ^{c} ± 0.01	1.90 ^{bc} ± 0.01	1.59 ^{c} ± 0.03	2.29 ^{b} ± 0.01	2.90 ^{a} ± 0.23
POP	1.41 ^{c} ± 0.01	1.46 ^{c} ± 0.02	1.88 ^{bc} ± 0.03	1.55 ^{c} ± 0.01	1.73 ^{c} ± 0.01	1.63 ^{c} ± 0.15	3.03 ^{ab} ± 0.48	3.89 ^{a} ± 0.88

Table 2. *Cont.*

	DN		KT		DI		AM	
Triacylglycerol (TAG) %	**2021**	**2023**	**2021**	**2023**	**2021**	**2023**	**2021**	**2023**
StOO	15.33 [g] ± 0.14	18.17 [f] ± 0.09	25.50 [ab] ± 0.01	26.45 [a] ± 0.02	23.02 [cd] ± 0.01	24.63 [bc] ± 0.06	21.05[e] ± 0.48	21.64 [de] ± 0.80
POSt	4.18 [a] ± 0.09	4.03 [a] ± 0.01	2.64 [a] ± 0.16	2.75 [a] ± 0.17	2.92 [a] ± 0.07	3.69 [a] ± 0.83	2.99 [a] ± 0.02	3.62 [a] ± 0.07
StLSt	13.88 [ab] ± 0.06	13.20 [bc] ± 0.23	11.61 [d] ± 0.05	11.26 [d] ± 0.16	14.45 [a] ± 0.17	14.31 [a] ± 0.36	13.03 [c] ± 0.32	12.96 [c] ± 0.23
AOO	1.91 [a] ± 0.17	1.92 [a] ± 0.02	2.08 [a] ± 0.01	2.14 [a] ± 0.03	1.85 [a] ± 0.06	1.82 [a] ± 0.02	1.71 [a] ± 0.42	1.68 [a] ± 0.28
StOSt	46.20 [a] ± 0.08	42.61 [b] ± 0.23	28.34 [d] ± 0.19	28.58 [d] ± 0.01	32.77 [c] ± 0.07	32.43 [c] ± 0.46	23.39 [e] ± 0.80	21.36 [f] ± 0.37
StOA	4.18 [a] ± 0.03	3.44 [b] ± 0.19	2.22 [cd] ± 0.02	1.93 [cd] ±0.17	2.46 [c] ± 0.28	2.18 [cd] ± 0.01	1.99 [cd] ± 0.03	1.71 [d] ± 0.07
OAA	0.72 [a] ± 0.01	0.62 [b] ± 0.03	0.42 [cd] ± 0.04	0.40 [cd] ± 0.01	0.42 [cd] ± 0.03	0.34 [d] ± 0.01	0.47 [c] ± 0.01	0.00 [e] ± 0.00
SUS (mono-unsaturated TAGs)	73.00 [a] ± 0.02	67.91 [b] ± 0.09	49.12 [d] ± 0.32	48.61 [d] ± 0.17	57.04 [c] ± 0.01	56.51 [c] ± 0.04	48.30 [d] ± 0.49	47.94 [d] ± 0.23
SUU (di-unsaturated TAGs)	24.40 [d] ± 0.17	27.91 [c] ± 0.16	40.31 [a] ± 0.20	40.91 [a] ± 0.06	36.33 [b] ±0.06	37.18 [b] ± 0.44	39.64 [a] ± 0.21	40.08 [a] ± 0.69
UUU (tri-unsaturated TAGs)	3.32 [c] ± 0.03	4.65 [c] ± 0.09	10.99 [a] ± 0.16	10.67 [a] ± 0.07	7.06 [b] ± 0.02	6.91 [b] ± 0.64	12.53 [a] ± 0.29	12.31 [a] ± 0.15

Note: Significant differences of means ($p \leq 0.05$) within a row are indicated by different letters.

3.5. Physicochemical Properties of MKF

3.5.1. SFC Melting Profile by p-NMR

Figure 3 shows solid fat content (SFC) melting profiles of the various MKFs measured at different temperatures ranging from 5 to 40 °C. Regardless of the harvest year, sample DN had the highest SFC melting profile, followed by DI, KT, and AM. This indicates that the fat extracted from DN is the hardest. As a result, the four fats have different consistencies. All samples have relatively high SFC at 20 °C (above 20%), indicating that MKF is solid/semi-solid at room temperature. All MKFs melted completely around 35 °C, except for DN, which melted around 38 °C.

Comparing the samples from the two harvest years (2021 and 2023), we observed that the fats completely melted at the same temperature regardless of the harvest year. However, despite presenting similar profiles, relative differences were observed in their SFC melting profiles. This difference was very pronounced for sample DN. Throughout measurement temperature ranges, the sample DN from the harvest of 2023 exhibited lower SFC compared to the one from 2021. For the DI sample, the harvest from 2023 had slightly lower SFC than that of 2022 over the entire range of temperatures measured, but the melting behaviour was very similar. The melting curves of KT and AM showed different trends compared to the two harvest years. For KT, Between 5 and 20 °C and up to 25 °C, the SFC of samples from 2023 was slightly higher than those from 2021, while the opposite trend was observed between 20 and 25 °C. Regarding AM, the Solid Fat Content (SFC) of the two different harvest years was almost the same between 5 and 15 °C, while between 20 and 30 °C, the SFC of the 2021 sample was higher than that of 2023. The different melting characteristics observed are consistent with the differences in composition.

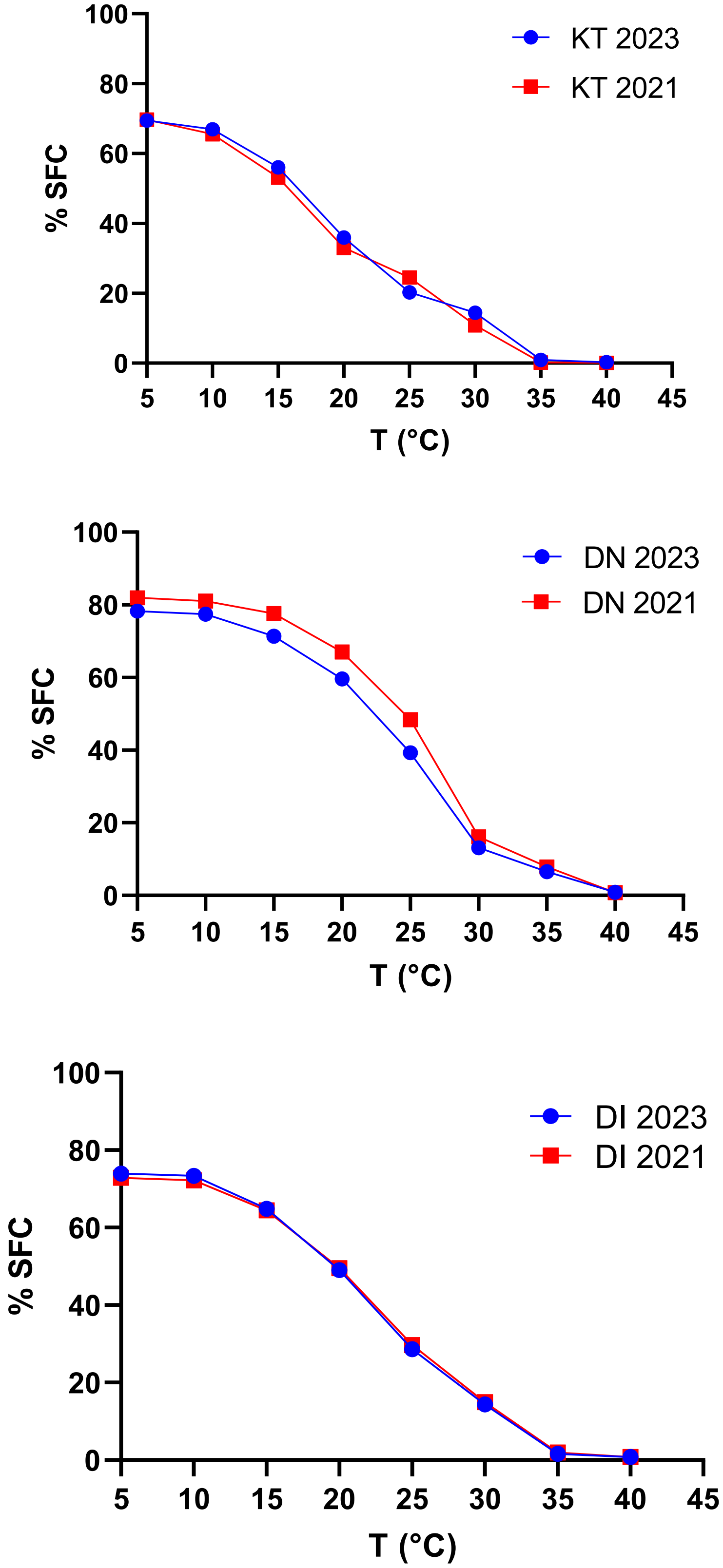

Figure 3. *Cont.*

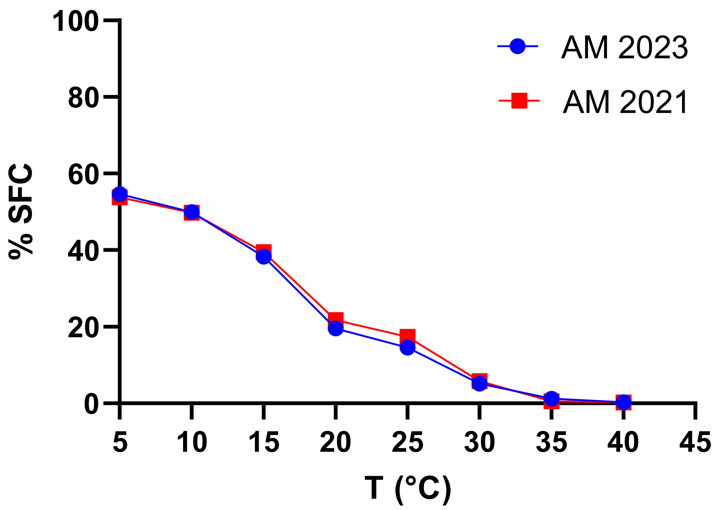

Figure 3. Effects of 2021 and 2023 harvest years on the p-NMR melting profiles of MKFs.

3.5.2. Melting Profile by Differential Scanning Calorimetry (DSC)

The DSC melting profiles of the four varieties of MKF are shown in Figure 4. Each of the melting curves was different with respect to the varieties of MKF. Multiple endothermic transitions were observed, corresponding to melting peaks of different TAG groups with different fatty acid compositions. In addition, four distinct melting point regions were generally evident: The very-low-melting-point (VLMP), low-melting-point (LMP), medium-melting-point (MMP), and high-melting-point (HMP) regions, along with shoulders, were observed, corresponding to the three main TAG groups (UUU, SUU, and SUS). Regardless of the harvest year, all samples exhibited similar melting profiles. The end of melting was observed around 35 °C for all samples, except for DN, which melted around 38 °C. However, relative differences in the contributions of the endothermic peaks were observed. These results were in agreement with the SFC melting profiles.

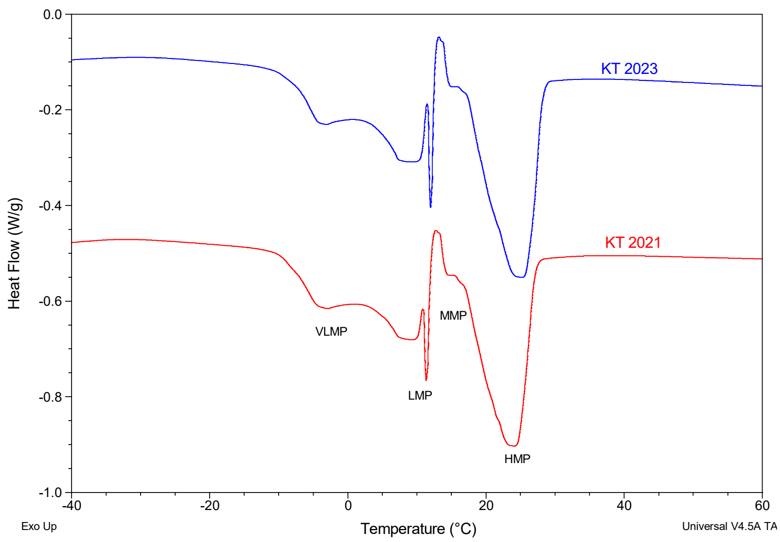

Figure 4. *Cont.*

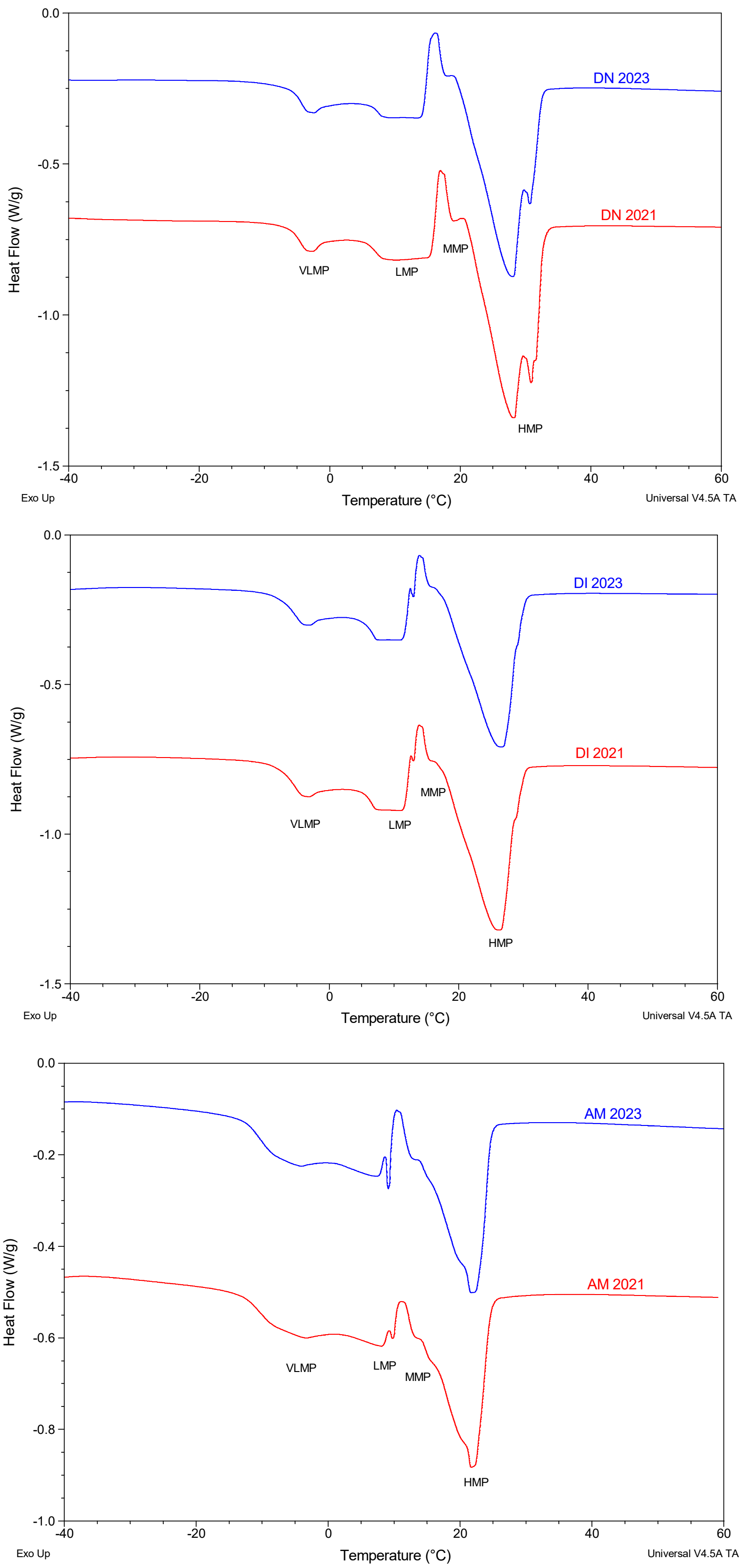

Figure 4. Effects of 2021 and 2023 harvest years on the DSC melting profiles of MKFs.

4. Discussion

This study aims to investigate whether the physicochemical properties of four Ivorian MKF varieties vary or not, depending on the harvesting year under specific climatic conditions. Mango trees are recognized for responding differently to weather variables, depending on the climate of the region in which they are cultivated [22,23]. MKF content, according to the literature, commonly ranges between 3.7 and 15% (on a dry basis), depending on the variety and growing conditions (origin, soil climate) [2,24,25]. This fat content is quite comparable to other fruit seeds, such as avocado seeds (*Persea americana*), which have an oil content ranging from 2 to 13% [26,27]. However, the diversity in oils/fats yield and composition emphasizes the unique properties and potential application of each type of seed oil/fat in various industries. In this study, variations in MKF content with respect to variety arose between the two non-consecutive harvest years due to differences in environmental conditions. Different trends were observed depending on the variety category. Traditional mango varieties (DN and DI) decreased their fat content in the second year (2023), whereas the opposite was observed in grafted or commercial varieties (KT and AM) (Figure 2). The behaviour of mango variety genotypes can be ascribed to the amount of available water during the important phenological stages in 2023 compared to 2021. In fact, the total rainfall (60.4 mm) that was measured during flowering, vegetative growth, fruit development, and maturity of the second year (2023) was lower than that recorded during the first year (82 mm). Note that in the Côte d'Ivoire, depending on the variety, flowering generally occurs in January and February, followed by fruiting in March and April [28]. Furthermore, although the temperatures of these two years were similar during these phenological stages, temperature variations of up to +1 °C were observed. Environmental changes during seed development and maturation can inhibit oil accumulation by affecting enzymes that convert carbohydrates to lipids [29].

Mango kernel fat (MKF) is mainly composed of stearic acid (24–48%), oleic acid (35–59%), palmitic acid (5–11%), linoleic acid (6–10%), linolenic acid (0.4–2%), and arachidic acid (1.8–2.5%) [2,30,31]. The fatty acid composition of the MKF extracted from the four Ivorian mango varieties exhibited typical proportions of major fatty acids commonly found in MKF (Table 1). The results of the study indicate that the composition of the fats was influenced by the year in which they were harvested. However, the set of varieties showed diversity in response. Since the variation in temperature during the two harvest years was slight, the rainfall between flowering and maturation of the fruit might be the most important factor influencing fatty acid composition. Palmitic acid and linoleic acid were sensitive to water stress (low rainfall) regardless of the mango variety, with a decrease in their proportion. The composition of mango seeds was also significantly affected by genetic and environmental factors, similar to what is observed in other oilseed crops [32,33]. In fact, the environmental conditions of the second harvest year (2023) favoured the accumulation of oleic acid and a decrease of stearic acid in the Djakoumankoun (DN) and Dadiani varieties (DI), while the trend was the opposite in the Kent (KT) variety. In contrast, the variety Amelie (AM) increased both oleic acid and stearic acid under the same environmental conditions. The literature shows that water stress at different phenological stages can lead to a reduction in oil content and has specific, clearly evident effects on the fatty acid composition of the oil [34,35]. In this regard, the decrease in stearic acid content in DN and DI and the increase in KT and AM during the second harvest year may, respectively, explain their lower and higher fat content compared to the first harvest year.

Triacylglycerol consists of three fatty acyl groups esterified to a glycerol backbone at positions sn-1, sn-2, and sn-3. In higher plants, TAGs predominate in the oil of seeds or fruits from oleaginous plants, primarily acting as an energy reserve to facilitate the growth of young seedlings during early germination stages [36]. These storage lipids hold significant nutritional and nutraceutical value, making them a widespread source of edible oils for human consumption. Unsurprisingly, environmental changes impacting fatty acid composition had a direct effect on the triacylglycerol profiles (TAG). As observed in the case of fatty acid composition, mango varieties also exhibited diversity in their responses to changes in environmental conditions regarding TAG composition. The relative decrease in stearic acid and the increase in oleic acid in DN and DI during the second harvest year resulted in a relative decrease in SUS content and a relative increase in SUU content in these varieties (Tables 1 and 2). The opposite trend of these fatty acids also led to an opposite trend in SUS and SUU in KT, associated with a decrease in UUU as well. The observed tendency of these fatty acids in AM also resulted in increased SUU content and decreased SUS and UUU content. Thus, these trends were observed when the mango trees were exposed to environmental change, likely due to the disruptions or alteration in biosynthesis pathways involved in TAG production. In fact, environmental stress affects the metabolism of fatty acid production and pathway metabolic involved TAG biosynthesis in vegetative tissues [36,37].

Solid fat content (SFC) is a crucial parameter that serves as a valuable indicator to determine whether a specific oil, fat, or blend is appropriate for a particular application [19,38]. It is linked with textural attributes (hardness, softness, and melting behavior) as well as sensory properties [39,40]. The studied MKFs exhibited different melting behaviours as well as hardness, depending on the varieties (Figure 3). Among the MKF sample, DN was the hardest. It was followed by DI, which was medium hard, then KT, which was soft, and finally AM, which was very soft. This difference in physical characteristics between the different varieties is preserved irrespective of the year of harvest. The differences observed in SFC melting behaviour are related to differences in fat composition. As described by Kouassi et al. [17], MKFs with high levels of saturated fatty acids, high proportions of monounsaturated TAGs (SUS, mainly StOSt), and low levels of tri-unsaturated TAGs (UUU) exhibited the highest SFC. These differences may provide numerous applications in the food, pharmaceutical, and cosmetic industries. Obviously, the physical characteristic differences observed between fats of the same variety from the two harvest years are due to differences in the TAG content. Thus, for DN, the lower SFC melting curve of the second harvest expresses a softer fat compared to that of the first harvest in 2021. This softening is linked to its lower SUS TAG (mainly StOSt) content and higher SUU and UUU contents. The fat from KT harvested in 2023 was slightly harder compared to that of 2021 due to its higher StOSt content. The samples of DI from the two different harvest years had almost overlapping melting profiles due to the very high similarity in SUS, SUU and UUU contents. However, that from 2021 is very slightly harder due to its slightly higher StOSt content compared to that of 2023. For AM, although the SFC of the fat from the 2023 harvest was slightly higher than that of 2021 between 5 and 15 °C, it melted faster due to its lower StOSt content.

DSC is a technique that has been widely used in the field of fats and oils for the authentication of oils and fats from both animal and plant sources [41]. It is the most widely used technique for thermal analysis of oils and fats and has been employed for monitoring the phase behaviour of TAG mixtures [42]. In this study, the fats from the four mango varieties exhibited different melting behaviour, which was specific to each variety (Figure 4). These thermodynamic characteristics are related to the qualitative and quantitative composition of TAGs. Thus, in relation to each variety, the melting profiles of the different samples harvested between the two years were similar, with differences in the contributions of the melting-point regions (Figure 4). As the melting-point regions are related to the three main TAG groups (UUU, SUU, SUS), these differences are obviously due to variations in their proportions. Although the impact of the harvesting year is not very visible on the DSC melting thermograms of samples collected in different years (Figure 4), differences are observed. These results are consistent with their SFC profiles, which also showed relative differences in physical characteristics.

5. Conclusions

The study investigated the effect of growing conditions in different harvest years on the physicochemical properties of mango kernel fat. The results revealed significant variability in MKF properties due to differences in climatic conditions between the years

2021 and 2023. The study observed that variations in physicochemical characteristics of MKF were influenced by environmental conditions, particularly rainfall, during crucial phenological stages. These variations were linked particularly to the amount of available water during flowering, vegetative growth, and fruit development stages, with lower rainfall in 2023 impacting the results. The study also found that the genetic characteristics of the mango tree significantly affect the chemical composition of MKF, similar to other oilseed crops. In general, during a lower rainfall period (60.4 mm), particularly during the important phenological stage, the fat content of traditional mango varieties reached 9.6 and 9.4 g/100 g for DN and DI, respectively. In contrast, during a high rainfall period (82.4 mm), the fat content was 9.4 and 8.4 g/100 g. Conversely, the grafted varieties, KT and AM, showed the opposite trend, with fat content of 7.6 and 4.9 g/100 g during the lower rainfall period increasing to 8.5 and 5.3 g/100 g during the higher rainfall period, respectively.

Regarding the fatty acid (FA) composition, lower water availability led to a decrease in palmitic and linoleic acids across all mango varieties. However, the response to rainfall for other fatty acids varied by variety. During the lower rainfall period, DN and DI exhibited increased accumulation of oleic acid at the expense of stearic acid, whereas this trend reversed during the high rainfall period. For KT, the response was the opposite, with oleic acid decreasing and stearic acid increasing with low rainfall. AM showed an increase in both fatty acids during the lower rainfall period and a reduction during the higher rainfall period. The research further demonstrates that environmental changes during seed development affect the triacylglycerol profiles. These changes influence the solid fat content (SFC) and melting behaviour of MKF, which are crucial properties for determining if the fats are suitable for potential applications in food, pharmaceutical, and cosmetic industries. Despite slight variations in temperature between the two years, rainfall emerged as a significant factor influencing FA and TAG composition. This highlights the importance of annual environmental factors in determining MKF quality. Although only two years were analysed, the results emphasise the need to consider specific annual conditions rather than the year itself. Therefore, these findings suggest that these factors must be considered in the implementation of a logistic chain. Standardization by blending fats from different varieties would minimize the physicochemical variations due to climate variations.

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