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Chemical composition and storage temperature influence on textural characteristics of bakery fats derived from plant sources

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Abstract. Edible fats obtained from plant sources, characterized by their higher proportion of saturated fatty acids, typically exist in solid or semi-solid states and present different physical properties. The quality of solid or semi-solid vegetable edible fats plays a crucial role in the food production sector and for consumers alike. Attributes such as fat hardness and spreadability are significant factors for both industry and consumers, as these textural properties are directly influenced by the constituents of the fats. The chemical composition and fatty acid content of fats derived from plant sources correlated with textural characteristics such as hardness, plasticity, adhesiveness, viscosity, and also spreadability properties were investigated. The total color differences of fat samples varied from 7.06 to 45.50. Among the saturated fatty acids, palmitic acid occurred as the predominant one across palm oil, and margarine samples, while the most abundant monounsaturated fatty acid was oleic acid with an average of 36.41% for palm oil and 26.46% for margarine samples. The puncture test performed with three different penetrometers, and the spreadability test, conducted at two different temperatures, showed a differentiation of the analyzed fat samples.

***Keywords*:** fats; fatty acids; texture; spreadability; PCA.

1. Introduction

Fats and oils, both types of triglycerides, exhibit different physical states at room temperature: fats are solid or semi-solid, while oils are liquid or clear. Together with carbohydrates and proteins, they constitute the three major classes of food. These substances serve as valuable nutrient sources and can originate from vegetables, animals, and marine organisms, providing approximately 9 kilocalories of energy per gram. Triglycerides, comprised of three fatty acid units and one glycerol unit, constitute the functional units of fats and oils [1]. Although the current dietary guidelines recommend that the intake of total fat be limited to 30% of calories, while the intake of saturated fat should be limited to 10% of the total energy intake [2], edible fats and oils play a decisive role in the human diet, providing essential fatty acids needed for growth and development, serving as a valuable source of concentrated energy, and desirable sensory qualities. Additionally, they function as carriers for fat-soluble vitamins (A, D, E, K) and as precursors for the production of β-carotene, steroid hormones, and prostaglandins [3]. Consuming a diet high in fat can lead to an excess energy intake and contribute to the onset of obesity, which is associated with the development of various diseases such as diabetes, hypertension, high blood cholesterol, and cardiovascular diseases. While the Dietary Guidelines for Americans (2015–2020) do not explicitly emphasize reducing total fat intake, they do advise limiting the consumption of trans fats and saturated fats. Furthermore, they advocate for the consumption of low-fat or fat-free foods as part of a comprehensive approach to promoting healthy living [2]. The edible fats are solid or semi-solid at room temperature due to their higher proportion of saturated fatty acids. Fats can present three polymorphic forms α, β, β', varying in energy, crystalline structure, and other properties, impacting the texture and consistency of products. Despite these differences, their chemical composition remains unchanged. Furthermore, milk fat, cottonseed, and palm oil tend to form β' crystals, whilst coconut oil, peanut, and palm kernel oil tend to form β crystals [3]. Animal and vegetable fats can be used at breakfast on a slice of bread, as a frying agent, for cooking, and in the process of bread making to aid in the leavening and to enhance the softness of the bread's crumb, or in the production of confectionery products, pastry, and ice cream [4, 5]. In the case of animal and vegetable fats hardness and spreadability are important qualities for both consumers and industry [6, 7]. The rheological and textural properties of solid or semi-solid edible fats are influenced by their constituents, especially solid fat content, where higher solid fat content leads to increased hardness and a lower degree of spreadability. Various evaluation methods, including instrumental and sensory analyses, are used to assess the spreadability and hardness of butter, margarine, mixtures of butter and vegetable fats, and shortenings [8]. The majority of instrumental techniques imply considerable deformations that break down the structure of the material, including penetration tests [6], texture profile analysis (TPA) [9], extrusion, compression, and

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shear tests. Additionally, small deformation methods are also utilized [8, 10]. Considering the above mentioned, the quality of solid or semi-solid vegetable edible fats has an important role both in food production and for consumers. Thus, this research aimed to investigate the chemical composition and fatty acid content of palm oil, margarine, and coconut oil closely correlated with textural characteristics such as hardness, plasticity, adhesiveness, and viscosity assessed using different penetrometers; also the spreadability of the investigated edible fats was evaluated. Furthermore, the color parameters were analyzed as part of the study.

2. Experimental

The experimental materials used in this study were represented by palm oil, margarine, and coconut oil. The margarine samples, palm oil and coconut oil were purchased from a national distributor of food ingredients and were intended for the bakery industry. The edible fat samples were stored in closed plastic containers in refrigerated conditions until further analysis [6].

2.1. Physicochemical analysis

The moisture and volatile matter content of edible fat samples was evaluated in accordance with ISO 662:2016 [11] using 5 g of sample and an oven set at 103 ± 2°C until a constant weight was attained. The fat content of analyzed samples was measured following the published method [6, 12], using the Randall technique and petroleum ether as extraction solvent. The obtained results were presented as mass percentages.

Color properties. For the determination of the samples' color properties, a Konica Minolta CR-400 Chroma Meter (Konica Minolta, Japan) was used, and the CIEL*a*b* ("Commission Internationale de l'Eclairage") method of uniform color space was applied [13]. The color parameters including brightness or luminosity (L*), red (+a*), green (-a*), yellow (+b*), and blue (-b*) were measured, whereas the tone or hue angle (h^0, Eq. 1), color intensity (C*, Eq. 2), whiteness indexes (WI, Eq. 3), yellowness indexes (YI, Eq. 4), and color total differences (ΔE*, Eq. 5) were the calculated color parameters [14-15]. The calibration was made with a white standard porcelain plate, using C illuminant and a 2° observer.

$$h^0 = \tan^{-1}(b^*/a^*) \quad (1)$$

$$C^* = \sqrt{a^{*2} + b^{*2}} \quad (2)$$

$$WI = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}} \quad (3)$$

$$YI = 142.86 \cdot b^*/L^* \quad (4)$$

$$\Delta E^* = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{1/2} \quad (5)$$

2.2. Fatty acid composition analysis

The lipids were extracted from the fat samples at 50 °C (ISO 14156:2001; ISO 661:2003). A mass of 0.1 g of extracted lipids was solubilized in *n*-hexane and then in the presence of 200 µL potassium hydroxide (2 mol/L) methanolic solution the fatty acids methyl esters (FAMEs) were obtained [18]. A mix standard (FAME Mix, Restek, Bellefonte, PA, USA) of 37 fatty acids methyl esters were used, and the identification of samples FAMEs involved the retention times comparison [19]. A gas chromatograph-mass spectrometer (GC-MS QP 2010 Plus, Shimadzu, Kyoto, Japan) equipped with an AOC-01 auto-injector and a SUPELCOWAXTM10 (Supelco Inc., Bellefonte, PA, USA) capillary column (length of 60 m, diameter of 0.25 mm, and film thickness of 0.25 µm) was used to determine the samples' FAMEs. Additionally, the obtained spectra were confronted with the GC-MS database spectra (NIST MSSearch 2.0) and the FAMEs quantification (*1*) assumed the peak areas determination [6, 20].

$$w = \frac{A_{sample} * c_{standard} * F * V_{final\ of\ sample}}{A_{standard} * m_{sample}} \quad (6)$$

where: c represents the concentration of each fatty acids methyl ester of the 37 component mix standard, A represents the area of the fatty acid peak, F represents a correction factor;

The atherogenicity index (IA) of fat samples was calculated based on fatty acids' composition following the Ulbritcht and Southgate formula [21]:

$$IA = \frac{(lauric\ acid + 4 * myristic\ acid + palmitic\ acid)}{unsaturated\ fatty\ acid} \quad (7)$$

All reagents used for the analysis were from Sigma Aldrich (Darmstadt, Germany).

2.3. Texture and spreadability analysis

The textural analysis of vegetable fats was evaluated with a texture meter from Mark 10 ESM 301 (Mark 10 Corporation, Copiague, NY, USA). Three different penetrometers were utilized, each with distinct geometries: a 120° conical penetrometer with a 4 mm penetration (PC_{120}), a 5 mm diameter spherical penetrometer with a 2 mm penetration (PS_5), and a 10 mm diameter spherical penetrometer with a 4 mm penetration (PS_{10}). For the textural analysis, the fat samples were stored at 20±2 °C for 12 hours and then placed in cylindrical plastic containers with 35 mm diameter and 35 mm height (Figure 1), without creating bubbles in the fat structure. Half of these containers were analyzed in 2 hours, while the remaining half was stored at 10±2 °C for 24 hours and then subjected to textural analysis. The testing speed was set at 10 mm/min, while the MESUREgauge software was used for data collection. The evaluated texture parameters included hardness (H), plasticity (P), adhesiveness (A), and viscosity (V) [6, 19]. Hardness was determined as the maximum force (Newtons) recorded at the end of the load, whereas the positive area or work under the load curve represented plasticity (P) expressed as N·mm or mJ. Adhesiveness was quantified as the negative area under the force-penetration depth curve (A, N·mm or mJ), whereas viscosity was calculated as the negative peak force (Newtons) [22, 23].

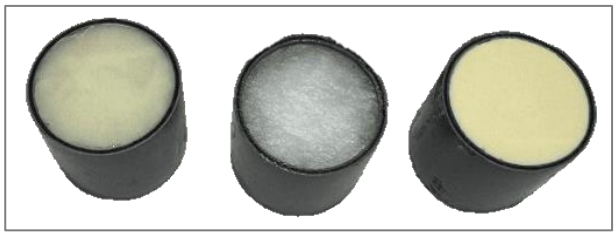

Figure 1. Edible fat sample (palm oil, coconut oil, and margarine)

Spreadability evaluation. The spreadability characteristics of fat samples were evaluated with a Spreadability Rig attachment and a 500 N load cell (Mark 10 Corporation, Copiague, NY, USA). The sample preparation respected the same protocol presented above with the mention that the edible fat samples were placed in a female cone with an angle of 90°. The samples were analyzed using an appropriate male cone (90° angle, diameter of 32 mm, and height of 16 mm) with a penetration depth of 14 mm. The testing speed was set at 10 mm/min, while the MESUREgauge software was used for data collection (force - N vs. displacement - mm). From the force-displacement curves, firmness/hardness, spreadability, and adhesiveness were determined. The spreadability of fat samples was calculated as the area under the loading force deformation curve [8, 24, 25].

2.4. Statistical analysis

The sample was differentiated through an analysis of variance (One-Way ANOVA) conducted with a significance level (α) of 0.05, using Statgraphics Centurion XVI software. Multiple comparisons of means were then carried out using Fisher's least significant difference (LSD) at a confidence level of 95%. The Pearson correlation analysis was executed utilizing SPSS 16 software, developed by SPSS Inc. in Chicago, IL, while Principal Component Analysis (PCA) was carried out using OriginPro software.

3. Results and discussion

3.1. Physicochemical and color evaluation

In Romania, the intake of plant-based fats is higher than that of animal-based fats. In recent years, consumption of plant-based fats increased by 6.4%, reaching 18.3 kg in 2020, oil representing 79% in 2014 and 85.2% in 2020, whereas solid vegetable fats ranged between 21% and 14.8%. Notably, there was a significant decline in margarine consumption, decreasing from 3.4 kg to 2.7 kg [26]. According to Salas [27] liquid oils, commonly utilized in retail, frying, canning, and the preparation of emulsions or margarine, represent approximately three-quarters of global vegetable lipid production, while solid fats, predominantly serving industrial purposes as raw materials for structured lipids and confectionery fats, which form the foundation of a wide array of food products, represent less than a quarter of the world's vegetable lipid. The principal sources of solid vegetable fats are represented by palm stearins, palm kernel oil, cocoa butter, coconut oil, mango, shea, kokum, or illipe. Figure 2 presents the average fat and moisture results of analyzed vegetable fat samples. The fat content ranged between 69.50% and 99.20 %, while the moisture and volatile matter content varied from 30.18% to less than 1%. Palm oil and coconut oil showed the highest fat content (99.03% and 99.18%) while the moisture and volatile matter content presented low values. Moisture and volatile matter content stand out as critical factors in determining fat and oil quality, maintaining a low moisture content is advantageous as it prolongs shelf life by preventing oxidation and rancidity processes [28, 29]. The margarine samples presented higher values for moisture and volatile matter content - 29.91%, whereas the average fat content was 69.82%. According to Zevenbergen [30], margarine holds the largest volume and widest distribution among the products derived from vegetable oils and fats, furthermore, in 2020 the total global production of edible-grade coconut oil was 3.57 million tons, the top three producers being the Philippines, Indonesia, and India [28].

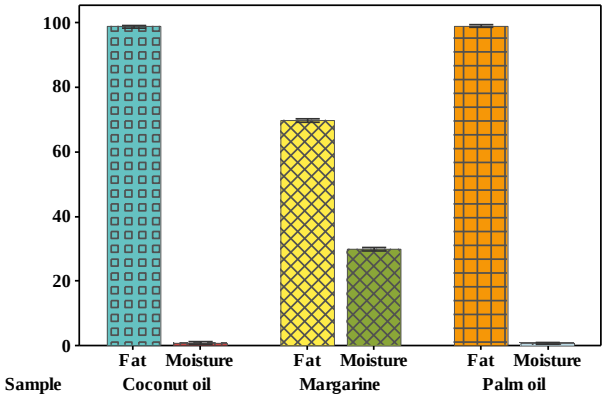

Figure 2. Physicochemical results of vegetable fat samples: coconut oil, margarine, and palm oil.

Color evaluation of oils and fats is a usual and critical parameter for both processors and consumers. For many years, the color of vegetable oils and fats was indicated for production and trade by red and yellow Lovibond values [31]. In the present study, the color evaluation was made with the CIE L*a*b* - "Commission Internationale de l'Eclairage" - uniform color space method. According to Endo [5], the color of edible fats and oils can be influenced by chlorophyll pigments and phospholipids content. Table 1 and Table 2 show the measured and calculated results of evaluated fat samples. As can be seen, the brightness – L* varied from 59.74 to 91.25, margarine sample presented the highest values, being similar to those reported by Pădureț [6] and close to that stated by Smetana *et al*. [7]. The coconut oil presented the lowest values of brightness. All the a* color parameters (red (+a*) – green (-a*) axis) showed negative values, suggesting a leaning towards a green color of analyzed fat samples, whereas the b* color parameter (yellow (+b*) – blue (-b*) axis) showed positive values only for margarine and palm oil, indicating a leaning towards a yellow color. According to Ogori [1], carotenes such as lycopene, and xanthophylls such as lutein influence fats and oils' yellow color, whilst chlorophyll, a green pigment found in plants, can impart a green color. Among common vegetable fats and oils, canola oil typically has the highest levels of chlorophyll. In contrast, the coconut

oils b* color parameter had negative values with an average of -0.73 showing a tendency of the samples towards a blue color. The ANOVA statistical analysis categorized all the color results, both measured (L*, a*, and b*) and calculated one (C, h^0, YI, and WI), into three distinct statistical groups (a-c) with $p < 0.001$, emphasizing the divergence in visual characteristics among the vegetable fat samples. The hue angle or tone (h^0) ranged between 94.27 and 223.58 and was expressed in sexagesimal degree. It can vary from 0° to 360°, representing the dominance of the spectral component, such as red (0°/360°), yellow (90°), green (180°), or blue (270°). The hue angle results for palm oil (111.25) and margarine (94.27) are in the second quadrant between yellow (90°) and green (180°), which supports the above-mentioned, while the hue angle of coconut oil (223.58) was in the third quadrant between green (180°) and blue (270°). Taking into account the color intensity or colorfulness (C*) results it can be observed that the smallest value was calculated for coconut oil samples indicating a clear or water-like color [32]. Additionally, alongside the previously mentioned parameters, the whiteness index (WI) and yellowness index (YI) were also computed. Notably, the margarine samples exhibited the highest yellowness and whiteness indexes among the analyzed samples (31.52 and 77.92). The lowest yellowness whiteness indexes were recorded for coconut oil samples, while the palm oil and margarine samples presented close values of the whiteness index.

Additionally, the total color differences (ΔE*) between analyzed fat samples were calculated and the corresponding results are displayed in Table 2. Total color differences serve as a crucial and valuable parameter for evaluating variations in food color. The total color differences of vegetable fat samples varied from 15.44 to 37.80. Furthermore, the human eye can readily discern color differences between analyzed samples when the ΔE* value exceeds 3. Minor color differences can be distinguished by human observers for ΔE* values between 1.5 and 3, however, if ΔE* drops below 1.5, the color differences become imperceptible to the human eye [14, 19].

Table 1. The CIE L*a*b* color parameters of vegetable fats

Sample	Color parameters- mean (SD)						
	L*	a *	b*	C*	h^0	YI	WI
Palm oil	79.01b (0.94)	-4.34c (0.06)	11.16b (0.49)	11.97b (0.47)	111.25b (0.60)	20.18b (1.04)	75.84b (0.97)
Coconut oil	59.74c (2.96)	-0.77a (0.05)	-0.73c (0.10)	1.06c (0.09)	223.58a (3.73)	-1.76c (0.32)	59.73c (2.96)
Margarine	91.25a (2.26)	-1.50b (0.10)	20.13a (0.53)	20.19a (0.53)	94.27c (0.18)	31.52a (0.31)	77.92a (0.50)
p	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$	$p < 0.001$

Different lowercase letters across columns (L*, a*, b*, C, h^0, YI, WI) denote a notable difference in average values ($p < 0.05$), as determined by one-way ANOVA analysis. L* - brightness, a* - red/green, b* - yellow/blue, C* - color intensity, h^0 - hue angle, YI yellowness index, WI - whiteness index. SD - standard deviation.

Consequently, the total color differences between vegetable fat samples can be easily perceived by the human eye. Among the values displayed in Table 2, only the difference between palm oil and margarine is smaller (15.44). The color difference results underwent statistical analysis, revealing a significant difference among the samples at a significance level of $p<0.01$, as indicated by the ANOVA.

Table 2. The CIE L*a*b* total color differences of vegetable fats

	Palm oil	Coconut oil	Margarine
Palm oil	-	22.92	15.44
Coconut oil	-	-	37.80
Margarine	-	-	-

3.2. Fatty acid composition analysis

According to previous research [33], vegetable oils and fats like sunflower, soybean, and palm along with fish, poultry, pork, and beef are the most prevalent food sources abundant in fats and fatty acids; coconut oil, cottonseed oil, palm oil, and palm kernel oil are rich in saturated fat and typically exhibit a thicker or partially solidified consistency at room temperature [27]. The concentration of fatty acids in the fat fraction of vegetable fat samples is presented in Table 3 as percentages. Out of the 37 fatty acids analyzed, only 17 were quantified. These 17 quantified fatty acids were categorized into four groups based on chain length and degree of unsaturation: short- and middle-chain saturated, long-chain saturated, monounsaturated, and polyunsaturated. As can be seen for the coconut oil samples the short and middle-chain saturated fatty acids constitute a substantial portion of the overall composition (57.07%), the lauric acid being the most abundant fatty acid (48.24%). Additionally, long-chain saturated fatty acids emerge as significant constituents, with an average value of 36.39%. Correspondingly to Rahim [34] lauric acid dominates the composition of fatty acids, accounting for a majority proportion ranging from 46% to 48%, being extensively used in both the food and industrial sectors due to its high concentration of short and middle-chain fatty acids and because it is easy to digest. In the case of margarine samples (Figure 3) the short and middle-chain fatty acid content presented lower values with a mean of 6.74% similar to those stated by [35] for Bulgarian margarine. In contrast to coconut oil, the palm oil samples showed the lowest short and middle-chain fatty acid concentrations. In the

long-chain saturated group, all vegetable fat samples stood out through a high content of fatty acids; the palm oil samples presented the highest content (53.38%) closely followed by margarine samples (50.24%), whereas the coconut oil samples presented lower values. Among the saturated fatty acids measured (short and middle-chain and long-chain saturated categories), palmitic acid occurred as the predominant fatty acid across both palm oil and margarine samples. Specifically, the analyzed palm oil samples presented the highest concentration of 48.98%, the margarine samples exhibited a lower concentration of 38.66%, while the lowest concentration of 12.40% was observed in the coconut oil samples. As per Kandhro and Pădureț [6, 36], the outcomes regarding palmitic acid indicate a significant impact of palm oil in the manufacturing of margarine. Regarding the palmitic acid content of palm oil samples, similar results were reported in other studies [34, 37], additionally palm oil contains significant amounts of tocotrienol (vitamin E), and since it possesses physical properties of solid fat, finds application in food products requiring high solid fat content such as margarine, shortening, and vanaspati, but food manufacturers often prefer palm oils due to their ease of maintaining flavor and consistency in processed foods. Conversely, palm oil also serves to provide solid fat functionality without the need for hydrogenation and does not contain trans fats. In the monounsaturated fatty acids group, the most abundant fatty acid for palm oil and margarine samples was oleic acid with an average of 36.41% and 26.46%, while for the coconut oil samples only the oleic acid (5.56%) was quantified. Furthermore, palm oil and margarine samples presented significant amounts of polyunsaturated fatty acids like linoleic and γ-linolenic acids. The linoleic fatty acid was quantified in all analyzed vegetable fat samples being the abundant one, varying from 0.92% (coconut oil) to 14.30% (margarine), while palm oil presented intermediate values of 9.97%, similar to those reported in other studies [34, 38]. The γ-linolenic acid was not detected in margarine and coconut oil samples. The European Food Safety Authority (EFSA) report recommends a daily intake of 10 grams of linolenic acid for adults and no specific value for the (n3)/(n6) ratio was established [39]. Solid fats offer numerous technological advantages over oil in the food industry due to their greater oxidative stability, improving the texture, spreadability, shelf life, and taste of food products. Recently, natural saturated fats from oil fractionation, especially palm oil, have replaced trans-fats in food manufacturing; palm oil, the most abundant vegetable oil globally, provides cost efficiency, high oxidation stability, and prolonged shelf life compared to other vegetable oils. In bakery production, most fats need to be solid or semisolid at room temperature to aid in batter handling, requiring a higher content of saturated fatty acids [40, 41].

Table 3. Fatty acids composition (%) present in the fat fraction of vegetable fat samples

Name	Abbreviation	RT ± 0.50 min	Mean values (SD)		
			Palm oil	Coconut oil	Margarine
Caproic	C6:0	7.84	-	0.38 (0.08)	-
Caprylic	C8:0	10.73	-	4.88 (0.51)	0.88 (0.10)
Capric	C10:0	14.14	-	3.57 (0.34)	0.79 (0.11)
Lauric	C12:0	17.52	0.06 (0.01)	48.24 (2.51)	5.07 (0.21)
Short and middle-chain saturated			0.06	57.07	6.74
Myristic	C14:0	20.67	0.32 (0.04)	19.41 (1.90)	3.65 (0.23)
Pentadecanoic	C15:0	22.18	-	-	0.15 (0.02)
Palmitic	C16:0	23.81	48.98 (2.56)	12.40 (1.02)	38.66 (1.87)
Heptadecanoic	C17:0	25.60	0.03 (0.01)	-	0.22 (0.01)
Stearic	C18:0	27.70	3.98 (0.21)	4.58 (0.57)	7.56 (0.14)
Behenic	C22:0	37.60	0.07 (002)	-	-
Long-chain saturated			53.38	36.39	50.24
Tetradecenoic (Myristoleic)	C14:1	21.30	-	-	1.70 (0.12)
pentadecenoic	C15:1 (cis-10)	22.86	-	-	0.12 (0.02)
Palmitoleic	C16:1	24.36	0.04 (0.02)	-	0.39 (0.03)
Oleic	C18:1 cis (n9)	28.33	36.41 (2.10)	5.56 (1.04)	26.46 (1.79)
11-Eicosenoic	C20:1 cis (n9)	33.32	0.03 (0.01)	-	-
Monounsaturated			36.48	5.56	28.67
Linoleic	C18:2 cis (n6)	29.60	9.97 (1.23)	0.92 (0.41)	14.30 (1.23)
γ-Linolenic	C18:3 (n3)	31.54	0.08 (0.02)	-	-
Polyunsaturated			10.05	0.92	14.30
Unsaturated/saturated fatty acids			0.87	0.07	0.75
Atherogenicity index			1.08	21.34	1.36

SD—standard deviation.

Table 3 also presents the unsaturated/saturated fatty acids ratios and the indices of atherogenicity (AI). These two indicators serve as metrics for assessing the potential impact of individual fatty acids on human health. They provide useful information regarding the probability of increased occurrences of conditions such as atherosclerosis and atheroma development. The unsaturated/saturated fatty acids ratio of analyzed vegetable fat samples varied from 0.07 to 0.87, the smallest values being calculated for coconut oil samples while the margarine and palm oil samples presented close values. According to the World Health

Organization recommendations (WHO) [42], the unsaturated fatty acids/saturated fatty acids ratio should be higher than 1.6, consequently, all vegetable-fat samples presented a much smaller ratio. The atherogenicity index evaluates the balance between main saturated fatty acids (such as lauric, myristic, and palmitic acids) categorized as proatherogenic (promoting the adhesion of lipids to cells within the circulatory and immunological systems), and unsaturated fatty acids categorized as antiatherogenic and offer a more comprehensive assessment of how fatty acids may impact the occurrence of pathological events [21].

The coconut oil samples showed the highest atherogenicity index whereas the margarine and palm oil samples presented a twenty times lower index (1.08 and 1.36). Correspondingly to Chen and Liu [43], the atherogenicity index of seaweeds is influenced by species and ranges between 0.03 and 3.58, the atherogenicity of fish and meat varies from 0.21 to 1.41 and from 0.165 to 1.32, while the atherogenicity index of dairy products exhibit values ranging from 1.42 to 5.13.

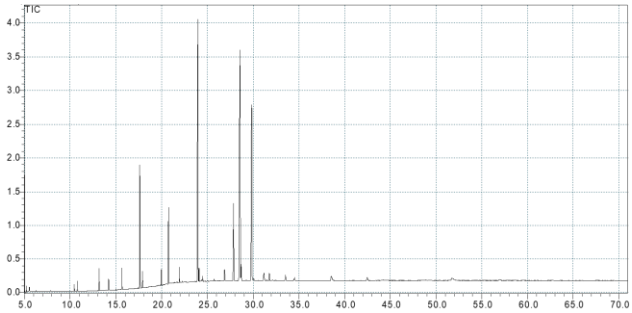

Figure 3. The chromatogram of the margarine sample

3.3. Texture and spreadability evaluation

Food texture represents all the mechanical geometrical and surface properties of solid or semi-solid food products. Due to their chemical composition, vegetable fats contain a higher proportion of saturated fatty acids leading to a solid or semi-solid consistency. In the case of margarine, spreads, and butter, the most significant texture parameters for consumers are represented by hardness and spreadability [8] and according to Rios [4], textural characteristics of fats that occur from their molecular states are of main importance. Considering that the fat samples belong to the category of plastic food materials, another fundamental parameter is represented by the mechanical work associated with plastic deformation, commonly referred to as plasticity. Consequently, Table 4 and Table 5 show the results of textural and spreadability measurements performed at different temperatures (10±2 °C and 20±2 °C).

The textural proprieties of analyzed fat samples were hardness, viscosity, plasticity, and adhesiveness assessed with three different penetrometers (PS_5 - 5 mm diameter spherical penetrometer, PS_{10} - 10 mm diameter spherical penetrometer, PC - conical penetrometer). It can be observed that the textural results of analyzed vegetable fat samples were influenced by the used penetrometer type, storage conditions, and also by sample category. For both temperature conditions, the highest values were registered with the conical penetrometer, while the lowest values were obtained with the 5 mm spherical one. The 10 mm spherical penetrometer presented textural results much larger than those registered with the 5 mm spherical one but closer to those registered with the conical penetrometer. The hardness and plasticity of vegetable fat samples kept for 24 h at refrigeration temperature (10±2 °C) measured with the three penetrometers varied greatly, from 1.12 N to 55.51 N and from 1.02 mJ to 73.95 mJ, being influenced mainly by the geometry of the penetrometer and fat origin.

The classification of the analyzed samples according to the hardness and plasticity evaluated with the three penetrometers is similar: H/P of coconut oil > H/P of palm oil > H/P of margarine. In contrast, the hardness and plasticity of fat samples stored at room temperature for 12 h (20±2 °C) displayed much lower values when measured using three different penetrometers, ranging from 0.02 N to 5.50 N and from 0.01 mJ to 6.65 mJ. The hardness and plasticity of coconut oil stored at 20±2 °C and measured with the 5 mm spherical penetrometer showed values close to zero.

Table 4. The mean (SD) texture parameters of analyzed fat samples.

Probe	**Fat Sample**	**10±2 °C - refrigeration**				**20±2 °C- room temperature**			
		H (N)	**V** (N)	**P** (mJ)	**A** (mJ)	**H** (N)	**V** (N)	**P** (mJ)	**A** (mJ)
PS_5	Palm oil	4.43 (0.15)	1.08 (0.21)	3.78 (0.06)	0.16 (0.10)	0.36 (0.01)	0.18 (0.01)	0.34 (0.01)	0.20 (0.01)
	Coconut oil	5.53 (0.57)	1.11 (0.28)	4.76 (0.82)	0.18 (0.07)	0.02 (0.01)	0.02 (0.01)	0.01 (0.01)	0.03 (0.01)
	Margarine	1.12 (0.07)	0.49 (0.03)	1.02 (0.12)	0.33 (0.18)	0.20 (0.01)	0.10 (0.01)	0.21 (0.01)	0.10 (0.01)
PS_{10}	Palm oil	28.48 (0.78)	1.94 (0.18)	49.26 (0.87)	0.28 (0.09)	3.35 (0.12)	1.50 (0.10)	6.16 (0.20)	1.06 (0.21)
	Coconut oil	30.13 (0.58)	1.98 (0.86)	53.97 (4.91)	0.20 (0.10)	0.18 (0.01)	0.13 (0.02)	0.34 (0.01)	0.19 (0.04)
	Margarine	7.02 (0.12)	2.3 (0.21)	11.99 (0.21)	1.55 (0.01)	0.85 (0.03)	0.29 (0.03)	1.77 (0.15)	0.64 (0.02)
PC	Palm oil	35.98 (0.74)	6.12 (0.34)	52.81 (1.85)	0.74 (0.25)	5.50 (1.02)	2.28 (0.86)	6.65 (0.42)	1.88 (0.22)
	Coconut oil	55.51 (0.65)	4.43 (0.50)	73.95 (1.26)	0.31 (0.14)	0.31 (0.01)	0.13 (0.01)	0.35 (0.03)	0.26 (0.01)

Probe	Fat Sample	10±2 °C - refrigeration				20±2 °C- room temperature			
		H (N)	**V** (N)	**P** (mJ)	**A** (mJ)	**H** (N)	**V** (N)	**P** (mJ)	**A** (mJ)
	Margarine	12.51 (0.86)	4.52 (0.24)	16.29 (2.38)	1.83 (0.31)	1.94 (0.26)	0.40 (0.08)	2.26 (0.52)	0.56 (0.11)

PS5 - 5 mm diameter spherical penetrometer; PS10 - 10 mm diameter spherical penetrometer; PC - 120° conical penetrometer. H – hardness; V-viscosity; P – plasticity; A - adhesiveness. SD - standard deviation.

This variability was primarily influenced by the penetrometer's geometry and the source of the fat. Furthermore, the classification of the samples based on their hardness and plasticity, as determined by the three penetrometers, also showed a similar pattern: H/P of palm oil > H/P of margarine > H/P of coconut oil. In addition to plasticity, which governs spreadability, viscosity serves as another crucial texture parameter for lipids [44]. The highest values for viscosity were measured with the PC penetrometer, the palm oil presented the greatest value for both test temperatures (6.12 N and 2.28 N), whereas the margarine and coconut samples presented similar values for samples stored for 24 h at refrigeration temperature (10±2 °C), close values were also reported for butter with different fat content (0.24 N - 2.12 N) [19]. The spherical penetrometers showed a narrow variation in viscosity results, the samples refrigerated for 24 h presented values ranging from 0.49 to 2.3, while the samples stored at room temperature presented values ranging from 0.02 to 1.50. The registration of testing curves in force versus displacement allowed the calculation of adhesiveness as energy expressed in millijoules, being in accordance with Bourne [45] and ISO 11036:2020 [46]. The adhesiveness of the palm oil samples, as measured by three different penetrometers, exhibited higher values when stored at 20 degrees Celsius compared to those kept under refrigeration conditions (10±2 °C). The PC penetrometer recorded the highest adhesiveness, reaching 1.88 mJ. Based on the obtain results the conical and 10 mm spherical penetrometer are much more suitable for evaluating textural characteristics of fats.

The mean results of the vegetable fat samples' spreadability analysis at two different temperatures are shown in Table 5. The fat spreadability and hardness resulted from the spreadability test conducted at 10 °C and 20 °C respected the same classification of the analyzed samples according to the hardness and plasticity evaluated with the three penetrometers: at 10 °C S/H_S of coconut oil > S/H_S of palm oil > S/H_S of margarine, whereas at 20 °C S/H_S of palm oil > S/H_S of margarine > S/H_S of coconut oil. The coconut oil samples presented the highest spreadability and hardness values and the lowest adhesiveness measured at 10 °C (175.1N and 691.4 N·mm) and at the same time the lowest spreadability and hardness values measured at 20 °C. Correspondingly with Glibowski and Swenson [8, 25] the samples that spread more easily necessitated smaller forces to be displaced from the female cone, therefore, smaller values indicated smoother spreadability. The margarine samples have the highest spread capacity at 10 °C between analyzed samples, whereas at 20 °C the highest spread capacity was measured for coconut oil samples. Spreadability and hardness are essential aspects in the processes of rolling and folding dough, as well as in the technologies utilized to obtain different types of biscuits. The puncture test performed with three different penetrometers, and the spreadability test, both conducted at two different temperatures, showed a differentiation of the analyzed fat samples. In addition, Glibowski also [8] reported an important difference in spreadability and hardness results obtained for selected table fats evaluated at 5 °C.

Table 5. The mean (SD) spreadability test parameters of analyzed fat samples.

Sample	10±2 °C - refrigeration			20±2 °C- room temperature		
	H_S (N)	**S** (N·mm)	**A_S** (mJ)	**H_S** (N)	**S** (N·mm)	**A_S** (mJ)
Palm oil	111.2 (5.3)	619.3 (7.5)	3.5 (0.8)	24.7 (0.6)	79.7 (3.7)	6.8 (0.3)
Coconut oil	175.1 (6.2)	691.4 (9.1)	0.9 (0.3)	3.4 (0.1)	7.9 (1.1)	4.9 (0.2)
Margarine	38.1 (3.3)	169.9 (6.3)	7.3 (0.5)	13.1 (1.1)	36.2 (2.9)	13.8 (0.4)

H_S – hardness, S – Spreadability, A_S - Adhesiveness. SD—standard deviation.

To highlight the correlation between fatty acids composition and textural and spreadability results of analyzed fat samples a Pearson statistical analysis was performed. The hardness and plasticity evaluated with PS10 probe on refrigerated samples were negatively influenced by oleic fatty acid ($p<0.05$) and also by palmitoleic fatty acid ($p<0.05$), whereas the heptadecanoic fatty acid content was positively correlated with PS10 adhesiveness at the same level. The measured spreadability of vegetable fat samples stored at refrigeration was positively correlated with palmitoleic fatty acid concentration ($p<0.05$), and also with linoleic fatty acid content ($p<0.05$). Another positive correlation was detected through Pearson correlation analysis ($p<0.05$), indicating a significant relationship between palmitic fatty acid concentration and hardness, plasticity, and viscosity measured with a PS5 probe on fat samples kept at room temperature. The PS10 adhesiveness and spreadability were strong and positively influenced also by palmitic fatty acid concentration ($p<0.01$, $p<0.05$). The adhesiveness (A_S) was positively influenced by heptadecanoic and pentadecenoic fatty acids concentration ($p<0.05$, $p<0.01$). Additionally, both fatty acids and textural results were correlated between them.

Furthermore, to emphasize the distinctions among the analyzed vegetable and animal samples, and reduce the variables number, a Principal Component Analysis (PCA) was conducted. The PCA biplot results, including scores and loadings, are presented in Figure 3 and Figure 4. The Principal Component Analysis was conducted on the fatty acid composition and texture parameters

(puncture and spreadability test) of the analyzed fat samples stored at refrigeration (Figure 3) and at room temperature (Figure 4). For the refrigerated fat samples, Figure 3, the principal components explained all of the data variations (100%), PC1 explained 67.55%, while PC2 explained 32.45% of the data variation. In Figure 4 the principal components cover also all data of the data variations the first component PC1, explains 69.35% while the second component PC2, explains 30.65 %.

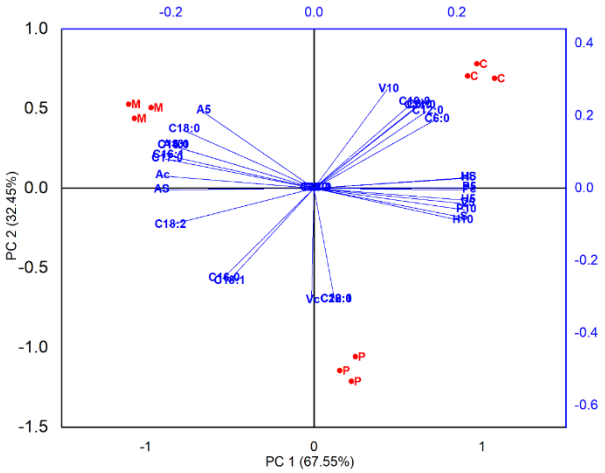

Figure 3. Principal component analysis (score and loading) of refrigerated (10±2 °C) fat samples: P - palm oil, C – coconut oil, M – margarine, H - hardness, V- viscosity, P - plasticity, A – adhesiveness, 5 - 5 mm diameter spherical penetrometer, 10 - 10 mm diameter spherical penetrometer, c - conical penetrometer, H_S - spreadability hardness, S - spreadability, A_S - spreadability adhesiveness.

The scores of the first PCA (refrigerated samples) distributed the fat samples in different quadrants, PC1 separated the coconut oil and palm oil from the rest of the samples, and PC2 separated the palm oil samples from the rest of the samples, the plasticity, spreadability and hardness exhibited a great influence in this distribution which is similar to those registered in textural (H, P) and spreadability measurement (H_S, S): coconut oil (C) - palm oil (P) - margarine (M). Similar results were displayed by the score of the second PCA analysis (Figure 4, samples kept at room temperature) which divided the samples following the same pattern as texture and spreadability results: palm oil (P) – margarine (M) - coconut oil (C). The central measured parameters within the correlation loadings matrix display a minimal impact on distinguishing between fat samples. Conversely, the outside measured parameters exert a significant influence on sample differentiation. Correspondingly, the Correlation Loadings of refrigerated fat samples show that the caproic (C6:0), caprylic (C8:0), capric (C10:0), lauric (C12:0) fatty acids, and also plasticity, hardness measured by puncture tests and spreadability hardness, spreadability influence directly the coconut oil projection. The same texture parameters had an indirect influence on the margarine samples projection, whereas the stearic (C18:0), palmitic (C16:0) fatty acids and adhesiveness evaluated by both texture and adhesiveness tests had a direct effect on margarine distribution. The cone viscosity had a direct influence on the palm oil projection. From the Correlation Loadings of fat samples stored at room temperature (20±2 °C), it can be observed that the fatty acids composition exhibited approximatively the same influence on samples projection. In contrast, the texture parameters evaluated by the puncture test and spreadability test presented a direct influence on palm oil projection and an indirect influence on coconut oil projection.

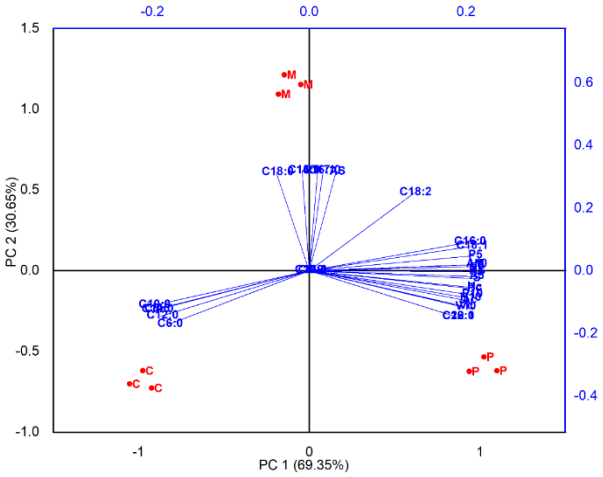

Figure 4. Principal component analysis (score and loading) of fat samples stored at room temperature 20±2 °C: P - palm oil, C – coconut oil, M – margarine, H - hardness, V- viscosity, P - plasticity, A – adhesiveness, 5 - 5 mm diameter spherical penetrometer, 10 - 10 mm diameter spherical penetrometer, c - conical penetrometer, HS - spreadability hardness, S - spreadability, AS - spreadability adhesiveness.

4. Conclusions

The study on edible fats obtained from plant sources highlighted that from evaluated color parameters, the measured color parameter represents a decisive factor in fat samples' discrimination. Furthermore, the ANOVA statistical analysis categorized the color results, whether measured or calculated, into distinct statistical groups with $p < 0.001$. This emphasizes the significant differences in visual characteristics observed among the vegetable fat samples. Color evaluation could potentially serve as a tool for detecting adulteration in solid fat. The short and middle-chain saturated fatty acids constitute a substantial portion of the overall composition for the coconut oil samples, the lauric acid being the most abundant fatty acid, whereas palmitic acid occurred as the predominant fatty acid across palm oil and margarine samples. The textural results of analyzed vegetable fat samples were influenced by the used penetrometer type, storage conditions, and also by sample category. For both temperature conditions, the highest values were registered with the conical penetrometer and the 10 mm spherical one. In the PCA analysis, the distribution of fat samples was similar to that registered at textural and spreadability measurement.

Conflicts of interest. The author declares no conflict of interest.

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