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Nutritional, Utility, and Sensory Quality and Safety of Sunflower Oil on the Central European Market

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Abstract: In the quality monitoring of 18 sunflower oil samples from the EU market, 14 were refined and 4 were cold-pressed. They demonstrated high quality of technological processing with low values of *trans*-unsaturated fatty acids, acid value, and peroxide value and also met the limits set by legislation in the content of process contaminants 3-monochloropropane-1,2-diol (3-MCPD) esters and glycidyl esters. Measurements of oxidative stability showed a difference in utility value. The average induction period of the oils from the traditional varieties was 2.6 h, predisposing them to cold cooking or short-term frying, while the 11.8 h of the four high oleic sunflower oils (HOSO) indicates the possibility of long-term heat stress. The nutritional benefit is the average vitamin E content of 663 mg/kg oil. The overall sensory quality of the samples was evaluated by a 12-member panel of trained assessors. On the seven-point category scale, the oils were of good to exceptional quality. The cold-pressed oils (CPOs) differed in having, on average, lower *trans*-unsaturated fatty acid content, process contaminants at unmeasurable levels, and, on average, higher vitamin E concentrations. The specific organoleptic properties of the CPOs were characterized by a pleasant nutty and sunflower seed flavor.

Keywords: composition of fatty acids; oxidative stability; acid value; peroxide value; 3-MCPD esters; glycidyl esters; organoleptic properties

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1. Introduction

Vegetable oils are an important part of a healthy diet. One of the most widely used in European households and gastronomy is sunflower oil because of its affordability and neutral taste. The oil is extracted from the seeds of the common sunflower (*Helianthus annuus* L.), a crop from the warm part of the temperate zone. The sunflower is native to the American continent, where it was domesticated by indigenous peoples several thousand years ago [1,2]. The seeds were brought to Europe in the 16th century, where their cultivation gradually spread. Total European Union (EU) oilseed production in marketing year 2022/2023 was 31,875 metric tons (TMT), where rapeseed was 19,620 TMT, sunflower seed was 9181 TMT, soybean was 2549 TMT, and other seeds was 525 TMT [3]. Europe's demand for sunflower seeds and products outstrips its domestic supply, which leads to significant imports. The EU traditionally sources about 50 to 70% of sunflower meal imports and 80–90% of its imports of sunflower oil from Ukraine. The EU's main sunflower producers are Romania, Bulgaria, and France [4]. Overall, with the global world production

of 19,840 TMT (for the 2021/2022 harvest), sunflower oil ranks fourth in edible oils, just behind palm, soybean, and rapeseed [5].

Current conventional varieties, based on traditional varieties, provide oils with a high proportion of linoleic acid (>50%). However, since the second half of the 20th century, many oilseeds have been bred to change the fatty acid content. Traditional selective (not genetic) breeding of sunflowers has resulted in new types of sunflower oils:

- High oleic sunflower oil (typically 80+% oleic acid), known as HOSO;
- Sunflower oil with a medium oleic acid content (typically 65%) and approximately 26% linoleic acid, known as mid-oleic sunflower oil;
- Sunflower oil with a high proportion of stearic acid (about 18%) and oleic acid (about 72%), known as high stearic/high oleic sunflower oil (HSHO) [6].

The utility value of these oils varies considerably. On the European market, we most often encounter traditional refined sunflower oil, which is characterized by relatively low oxidative stability. This makes it suitable for use in cold cooking as a salad oil or for short-term heat treatment of food by frying, stewing, or baking. In the food industry, it is used for the production of margarines and cooking fats or for the manufacture of mayonnaise. HOSO, on the other hand, is characterized by a very high oxidation stability and is therefore suitable for long-term industrial frying, including professional frying applications, e.g., in fast food chains or in industrial food applications. In retail packages, it is usually sold as a frying oil, either on its own or as a substantial part of it. It is comparable in oxidative stability to palm oil, but its lower saturated fatty acid (SFA) content makes it nutritionally superior. Medium oleic sunflower oil is popular especially in the USA and Canada. Due to its significantly better oxidative stability compared to traditional oil, it is also used for frying and deep-frying. The commercialization of HSHO is still in progress and is not yet widely available on the market. After fractionation, it is expected to be able to partially replace tropical fats in some types of food [7].

In industrial processing, sunflower oil is normally subjected to dewaxing (winterization) and refining. Refined sunflower oil finds widespread utility in the food, pharmaceutical, and cosmetic industries and culinary practices globally. In culinary contexts, refined sunflower oil serves as a staple for cooking and baking endeavors. With its neutral taste profile and high smoke point, it proves ideal for frying, sautéing, and deep-frying. Cold-pressed oil (CPO), with a light nutty flavor, is more of a specialty suitable for cold cooking [8]. On the market, the above types of oils can also be found as products of controlled organic farming (organic quality).

The nutritional evaluation of oils is based primarily on the fatty acid composition, because the dietary balance between different classes of fatty acids is important, particularly with respect to the risk of coronary heart disease [9]. Fat consumed should be primarily unsaturated fatty acids, with no more than 10% of total energy intake (E%) coming from saturated fatty acids and no more than 1 E% coming from trans-fatty acids, as strongly recommended by World Health Organization (WHO) guidelines. In its opinion on polyunsaturated fatty acids (PUFAs) published in 2010, the European Food Safety Authority (EFSA) recommended setting an adequate intake (AI) of n-6 PUFA linoleic acid (LA) at 4 E% and n-3 PUFA α-linolenic acid (ALA) at 0.5 E% and not setting a tolerable upper intake level or specific values for the n-3/n-6 ratio [10]. In this respect, sunflower oil is a rich source of unsaturated acids, and, with the exception of mid-stearic oil, also a minor source of SFA, as indicated above by oil type. As a result of the higher proportion of n-6 PUFA (traditional varieties) and the insignificant proportion of n-3 PUFA, it is nutritionally advisable to alternate the oil with other types of oil.

Of the minor compounds, the high α-tocopherol content of sunflower oil is the most nutritionally valuable. The literature states the range of tocopherols as 270–1240 mg/kg oil [11]. A sufficient intake of vitamin E is essential to prevent some neurological diseases resulting from vitamin E deficiency and probably also to prevent diseases related to oxidative stress [12]. In different countries worldwide, the recommended intake of vitamin E for an adult ranges from 7.5 to 15 mg per day [12–14], with the lowest values reported by the WHO

being 10 mg α-TE for men and 7.5 mg α-TE for women per day. In contrast, the highest values can be found in the USA, where the recommended daily intake of vitamin E (defined as the 2*R* isomers of α-tocopherol) for both men and women is 15 mg per day [13]. The EFSA set the adequate intake values for men at 13 mg and for women at 11 mg per day [12].

In fact, the composition of sunflower oil has already been studied in detail [15–19]. But complex studies addressing the technological, utility, and sensory quality for current European production are lacking. Therefore, the aim of this work was to fill this gap and to describe comprehensively the current state of the art, including toxicological safety given by compliance with legislative limits for process contaminants. This study is of major importance for public health, accurate dietary recommendations, food industry standards, and consumer awareness.

2. Materials and Methods

Samples of sunflower oils were purchased for laboratory testing in 2023 in Central European markets (Table 1). The sample set contained 18 products, of which 14 were refined and 4 were CPOs. All samples were at least 6 months prior to the best-before date at the time of analysis. The fatty acid content was determined after esterification to methyl esters (FAMEs) according to EN ISO 12966-2:2011 [20]. FAMEs extracted into hexane were analyzed by gas–liquid chromatography using an SP-2560 fused silica capillary column (100 m × 0.25 mm i.d., 20 µm film thickness) (Supelco, Bellefonte, PA, USA) in an Agilent 6890 gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) equipped with a flame ionization detector (FID) under the conditions described by Pohořelá et al. [21]. The fatty acid quantification was carried out by the internal normalization method, and the results were expressed as relative percentages of all identified fatty acids.

Table 1. List of sunflower oil samples from the market and their characteristics.

Sample No.	Cropping System	Origin of the Seeds	Oil Processing	Type of Oil	Best-Before Date (mm/yyyy)
1	Conventional	European Union	Refined	Traditional	June 2024
2	Conventional	European Union	Refined	Traditional	February 2024
3	Conventional	Ukraine	Refined	Traditional	March 2025
4	Conventional	Hungary	Refined	Traditional	February 2024
5	Conventional	Moldova	Refined	Traditional	May 2025
6	Conventional	Hungary	Refined	Traditional	July 2025
7	Conventional	Hungary	Refined	Traditional	May 2024
8	Conventional	Not specified	Refined	Traditional	July 2024
9	Conventional	Hungary	Refined	Traditional	May 2024
10	Conventional	Czech Republic	Refined	Traditional	May 2024
11	Conventional	Slovakia	Refined	Traditional	April 2024
12	Organic	European Union	Cold-pressed	Traditional	May 2024
13	Conventional	Serbia	Refined	Traditional	April 2024
14	Conventional	Czech Republic	Cold-pressed	Traditional	May 2024
15	Organic	Slovakia	Cold-pressed	HOSO *	November 2024
16	Organic	Slovakia	Cold-pressed	HOSO	October 2024
17	Organic	European Union	Refined	HOSO	May 2024
18	Conventional	European Union	Refined	HOSO	October 2024

* HOSO = high oleic sunflower oil.

Tocochromanols, i.e., α-tocopherol (α-T), β-tocopherol (β-T), γ-tocopherol (γ-T), δ-tocopherol (δ-T), α-tocotrienol (α-T3), β-tocotrienol (β-T3), γ-tocotrienol (γ-T3), and δ-tocotrienol (δ-T3), were determined by high-performance liquid chromatography (HPLC) (Streamline P1 non-steel pump; Watrex Praha, Prague, Czech Republic) with an amper-

ometric detector (HP 1049A; Agilent Technologies, Santa Clara, CA, USA) according to Fišnar [22]. The oil samples were dissolved in acetone (approximately 1 g with an accuracy of 0.1 mg per 100 mL). Conditions of HPLC analysis were as follows: mobile phase—methanol/acetonitrile (1:1, v/v) with $LiClO_4$ (0.02 mol/L) and NaCl (0.005 mol/L); flow rate—1 mL/min; injected volume—20 µL; column—Hypersil ODS, 200_4.6 mm, particle size—5 µm (Agilent Technologies, Santa Clara, CA, USA); column temperature—−28 °C (LCO 101 column heater; Ecom, Prague, Czech Republic); and detection potential—+0.7 V. The quantification was carried out by external calibration using the respective tocopherol standards. The content of vitamin E in α-tocopherol equivalents (α-TE) was calculated according to the formula [23] α-TE = α-T + 0.5 β-T + 0.1 γ-T + 0.03 δ-T + 0.3 α-T3 + 0.05 γ-T3. Use of the α-TE unit has been the accepted way of reporting vitamin E concentration in foods.

The oxidative stability of the oil samples was determined by the Rancimat test (Official Method AOCS Cd 12b-92 1993) [24] on a Rancimat apparatus (Metrohm, Herisau, Switzerland). The Rancimat method is based on accelerating the aging process of the sample by increasing its temperature and passing a continuous air current. The air flow transfers the volatile oxidation products from the sample vessel to a vessel containing distilled water. The instrument measures the conductivity of the water. A sudden, sharp increase in conductivity indicates induction time. An oil sample (2.5 g) was subjected to a constant temperature of 120 °C and an air flow rate of 20 L/h. The result was expressed as the induction period (IP) in hours.

The acid value (AV), which is defined as the mass of KOH (in mg) needed to neutralize the acids contained in 1 g of fat, was determined according to EN ISO 660 [25] by titration. The peroxide value (PV), which is expressed in milliequivalents of active oxygen required to oxidize potassium iodide under the relevant method conditions per kilogram of oil, was determined according to EN ISO 3960 [26] also by titration.

The content of MCPD esters and glycidol esters was determined by gas–liquid chromatography using a DB-5MS fused silica capillary column (30 m × 0.25 mm i.d., 0.25 µm film thickness) (Agilent Technologies, Santa Clara, CA, USA) in an Agilent 7820A gas chromatograph equipped with a quadrupole mass selective detector Agilent 5975 MSD (Agilent Technologies, Santa Clara, CA, USA) according to AOCS Official Method Cd 29a-13 [27]. The method is based on the conversion of glycidol esters to 3-monobromopropane-1,2-diol (3-MBPD) monoesters, acid transesterification of bound 3-MCPD or 3-MBPD, and GC/MS analysis of volatile phenylboronic acid derivatives. Deuterated diester of 3-MCPD with palmitic acid was used as the internal standard. The concentration was expressed as the amount of 3-MCPD, 2-MCPD, and glycidol, respectively, of the respective esters.

The organoleptic properties of the samples were assessed in the Sensory Laboratory of the University of Chemistry and Technology Prague, which is equipped according to the relevant international standard ISO 8589 [28] with a 12-member panel of trained assessors. The assessors were selected, trained, and monitored according to the international standard ISO 8586 [29], ISO 5496 [30], and ISO 3972 [31]. The assessors were also trained and experienced in evaluating edible oils and fats. A 100-point unstructured scale with 4 descriptors was used for the evaluation: overall pleasantness of odor, overall pleasantness of taste, pungent intensity, and overall off-flavor intensity, followed by a free qualitative description of the organoleptic characteristics. A seven-point category scale was used for the overall evaluation (1—very poor, 2—poor, 3—fair, 4—good, 5—very good, 6—excellent, 7—exceptional). RedJade software (RedJade Sensory Solutions, LLC, Martinez, CA, USA) was used for the collection of sensory analysis data and their statistical processing.

For all of the above measurements, two parallel determinations were performed for each sample. In order to verify the reliability of the results, six parallel determinations of the previously mentioned methods were performed for a selected sample. The repeatability, expressed as relative standard deviation (RSD), did not exceed 5% for any of the methods. Data obtained were then statistically processed using Microsoft Excel 2019 (Microsoft Corporation, Redmond, WA, USA) and Statistica (StatSoft, Inc., Tulsa, OK, USA) using

one-way analysis of variance with Scheffe's post hoc test. Differences were considered significant in all cases for a 95% confidence interval ($p < 0.05$).

3. Results and Discussion

3.1. Fatty Acid Composition

The basic characteristics of the oil composition were shown by their fatty acid profile (see Table 2). Samples 1–14, with a significant predominance of omega-6 linoleic acid, correspond to oils from conventional varieties, while samples 15–18, with a high oleic acid content exceeding 80%, correspond to HOSO oils. The percentages of all individual fatty acids were consistent with the range published in the literature [11]. According to the Codex Alimentarius standard [32], the oleic acid content of HOSO should be in the range of 75–90.7%, which these oils met. The content of omega-3 fatty acids, represented in sunflower oil only by α-linolenic acid, was nutritionally negligible. Only trace amounts (<0.1%) of *trans*-unsaturated fatty acids were present in CPOs, making them significantly different from refined oils according to Student's *t*-test ($p < 0.05$). Differences in deodorization parameters led to a slight increase [33,34], but this was still nutritionally insignificant (0.11–0.72%). Previously published studies reported that fatty acid composition affects the oxidative stability of fats and oils and that the rate of primary initiation of lipid oxidation increases with the proportion of PUFA in the fat [35,36].

Table 2. Composition of fatty acids in sunflower oils (as % of total fatty acids).

Sample No.	P	S	O	L	ALA	SFA	MUFA	PUFA	TFA
1	6.56 ± 0.13	3.44 ± 0.07	29.56 ± 0.30	57.08 ± 0.57	0.26 ± 0.03	11.53 ± 0.23	30.75 ± 0.62	57.40 ± 1.15	0.32 ± 0.03
2	6.23 ± 0.12	3.47 ± 0.07	28.40 ± 0.28	58.94 ± 0.59	0.09 ± 0.01	11.2 ± 0.22	29.47 ± 0.59	59.10 ± 1.18	0.23 ± 0.02
3	6.26 ± 0.13	3.37 ± 0.07	27.49 ± 0.27	59.59 ± 0.60	0.08 ± 0.01	11.14 ± 0.22	28.54 ± 0.57	59.83 ± 1.20	0.49 ± 0.05
4	6.49 ± 0.13	3.45 ± 0.07	25.66 ± 0.26	61.12 ± 0.61	0.08 ± 0.01	11.35 ± 0.23	26.70 ± 0.53	61.32 ± 1.23	0.63 ± 0.06
5	6.39 ± 0.14	3.18 ± 0.06	27.89 ± 0.28	59.51 ± 0.60	0.06 ± 0.01	10.95 ± 0.22	29.00 ± 0.58	59.65 ± 1.19	0.4 ± 0.04
6	7.06 ± 0.14	3.72 ± 0.07	27.61 ± 0.28	58.14 ± 0.58	0.07 ± 0.01	12.31 ± 0.25	28.77 ± 0.58	58.31 ± 1.17	0.61 ± 0.06
7	6.87 ± 0.14	3.63 ± 0.07	27.80 ± 0.28	58.77 ± 0.59	0.06 ± 0.01	12.00 ± 0.24	28.95 ± 0.58	58.89 ± 1.18	0.16 ± 0.02
8	6.96 ± 0.14	3.66 ± 0.07	27.21 ± 0.27	58.64 ± 0.59	0.10 ± 0.01	12.13 ± 0.24	28.39 ± 0.57	58.83 ± 1.18	0.65 ± 0.07
9	6.80 ± 0.14	3.71 ± 0.07	28.16 ± 0.28	57.80 ± 0.58	0.06 ± 0.01	12.12 ± 0.24	29.32 ± 0.59	57.93 ± 1.16	0.63 ± 0.06
10	6.27 ± 0.13	3.70 ± 0.07	32.34 ± 0.32	53.64 ± 0.54	0.80 ± 0.08	11.47 ± 0.23	33.81 ± 0.68	54.48 ± 1.09	0.24 ± 0.02
11	6.75 ± 0.14	3.64 ± 0.07	29.65 ± 0.30	56.86 ± 0.57	0.10 ± 0.01	11.95 ± 0.24	30.83 ± 0.62	57.00 ± 1.14	0.22 ± 0.02
12	6.45 ± 0.13	3.29 ± 0.07	28.19 ± 0.28	59.34 ± 0.59	0.08 ± 0.01	11.07 ± 0.22	29.39 ± 0.59	59.44 ± 1.19	0.09 ± 0.01
13	6.94 ± 0.14	3.66 ± 0.07	31.40 ± 0.31	54.39 ± 0.54	0.07 ± 0.01	12.11 ± 0.24	32.64 ± 0.65	54.53 ± 1.09	0.72 ± 0.07
14	6.39 ± 0.13	3.04 ± 0.06	23.30 ± 0.23	64.64 ± 0.65	0.07 ± 0.01	10.78 ± 0.22	24.40 ± 0.49	64.73 ± 1.29	0.09 ± 0.01
15	4.01 ± 0.08	3.20 ± 0.06	86.65 ± 0.87	2.64 ± 0.03	0.05 ± 0.01	9.15 ± 0.18	88.11 ± 1.76	2.70 ± 0.05	0.04 ± 0.01
16	4.03 ± 0.08	3.21 ± 0.06	83.77 ± 0.84	5.49 ± 0.05	0.04 ± 0.01	9.13 ± 0.18	85.24 ± 1.70	5.57 ± 0.11	0.06 ± 0.01
17	4.53 ± 0.08	2.73 ± 0.05	80.77 ± 0.81	8.37 ± 0.08	0.06 ± 0.01	8.98 ± 0.18	82.43 ± 1.65	8.47 ± 0.17	0.12 ± 0.01
18	4.10 ± 0.08	2.80 ± 0.06	81.30 ± 0.81	7.80 ± 0.08	0.26 ± 0.03	9.00 ± 0.18	82.80 ± 1.66	8.10 ± 0.16	0.11 ± 0.01

Values are expressed as mean ± standard deviation (SD); fatty acid: P = palmitic; S = stearic; O = oleic; L = linoleic; ALA = α-linolenic; SFA = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; TFA = *trans*-unsaturated fatty acids.

3.2. Tocopherols as Naturally Present Antioxidants

Tocochromanols (vitamin E, i.e., tocopherols and tocotrienols, especially α-tocopherol) are important lipophilic antioxidants in vivo that protect unsaturated fatty acids bound in tissue lipids from radical oxidation reactions. Their action is particularly indispensable for the protection of biomembranes and lipoproteins [23]. Adequate intake of vitamin E may be an important factor in the prevention and development of cardiovascular disease [37]. One of the most important and richest dietary sources of vitamin E is vegetable oils. The

content in α-TE averaged 645 mg/kg in samples of refined oil, while moderately higher contents were observed in cold-pressed samples, specifically 729 mg/kg (see Table 3). Both values corresponded to a range of 270–900 mg/kg refined oil and 270–1240 mg/kg cold-pressed oil, respectively, published in the literature [11,38]. The tocopherol content of CPOs was significantly different from refined oils according to Student's *t*-test ($p < 0.05$). The differences can be explained by the cultivar used and the environmental conditions during sunflower growth [39]. The refining conditions may lead to different final amounts of tocopherols in the refined oil. Major losses have been reported during the neutralization step, while other literature reported major losses in the deodorization step, reaching cumulative losses of 8.5–24% [15,38]. The α-tocopherol with higher antioxidant activity in vivo, consistent with the literature [11], strongly predominated in sunflower oil.

Table 3. Content of tocopherols and vitamin E in α-tocopherol equivalents and values characterizing quality of sunflower oils—acid value, peroxide value, and induction period.

Sample No.	α-Tocopherol [mg/kg]	Total Tocopherols [mg/kg]	Vitamin E (α-TE) [mg/kg]	Acid Value [mg KOH/g]	Peroxide Value [meq. O_2/kg]	Induction Period [h]
1	621 ± 3.1	649 ± 3.2	635 ± 3.2	0.19 ± 0.01	3.00 ± 0.09	2.77 ± 0.08
2	634 ± 3.2	658 ± 3.3	646 ± 3.2	0.14 ± 0.01	4.92 ± 0.15	2.74 ± 0.08
3	651 ± 3.3	673 ± 3.4	662 ± 3.3	0.15 ± 0.01	3.47 ± 0.10	2.87 ± 0.09
4	624 ± 3.1	646 ± 3.2	635 ± 3.2	0.16 ± 0.01	5.14 ± 0.15	2.49 ± 0.07
5	701 ± 3.5	723 ± 3.6	712 ± 3.6	0.13 ± 0.01	6.36 ± 0.19	2.44 ± 0.07
6	572 ± 2.9	587 ± 2.9	580 ± 2.9	0.15 ± 0.01	4.38 ± 0.13	2.39 ± 0.07
7	661 ± 3.3	682 ± 3.4	672 ± 3.4	0.18 ± 0.01	2.47 ± 0.07	2.86 ± 0.09
8	572 ± 2.9	591 ± 3.0	582 ± 2.9	0.12 ± 0.01	3.77 ± 0.11	2.92 ± 0.09
9	570 ± 2.9	590 ± 3.0	580 ± 2.9	0.14 ± 0.01	0.30 ± 0.01	2.78 ± 0.08
10	532 ± 2.7	584 ±2.9	558 ± 2.8	0.31 ± 0.02	0.23 ± 0.01	2.86 ± 0.09
11	688 ± 3.4	711 ± 3.6	700 ± 3.5	0.17 ± 0.01	0.19 ± 0.01	2.99 ± 0.09
12	796 ± 4.0	814 ± 4.1	805 ± 4.0	1.02 ± 0.05	0.23 ± 0.01	2.35 ± 0.07
13	695 ± 3.5	720 ± 3.6	708 ± 3.5	0.18 ± 0.01	3.96 ± 0.12	2.75 ± 0.08
14	772 ± 3.9	801 ± 4.0	787 ± 3.9	1.15 ± 0.06	4.16 ± 0.12	1.55 ± 0.05
15	704 ± 3.5	726 ± 3.6	715 ± 3.6	0.68 ± 0.03	2.53 ± 0.08	16.99 ± 0.51
16	598 ± 3.0	621 ± 3.1	610 ± 3.0	1.07 ± 0.05	3.19 ± 0.10	10.19 ± 0.31
17	670 ± 3.4	696 ± 3.5	683 ± 3.4	0.25 ± 0.01	3.87 ± 0.12	8.32 ± 0.25
18	660 ± 3.3	685 ± 3.4	673 ± 3.4	0.18 ± 0.01	1.83 ± 0.05	11.73 ± 0.35

Values are expressed as mean ± standard deviation (SD).

3.3. Free Fatty Acid Content

One of the tasks of refining is to reduce the free fatty acid content of oils. Their quantity reflects the AV. The measured lower AV values of refined oils (0.12–0.31 mg KOH/g), which were significantly different from those of CPOs (0.68–1.15 mg KOH/g), according to Student's *t*-test ($p < 0.05$), confirm this fact (see Table 3). According to the Codex Alimentarius standards for vegetable oils and animal fats, the acid value for refined vegetable oils should not exceed 0.6 mg KOH/g oil and 4.0 mg KOH/g for cold-pressed and virgin oils (except crude palm kernel oil and virgin palm oil) [32]. No sample exceeded this limit.

3.4. Peroxide Value

The hydroperoxide content as the primary product of the oxidative rancidity of fats is indicated by the PV. Since hydroperoxides are unstable intermediates, PV cannot generally be used as an accurate indicator of the degree of oil deterioration. In the case of heat-stressed fats, a decrease in PV can be expected due to the decomposition of hydroperoxides [40]. However, in the case of stored oils (not yet used), it is a good indicator of the degree of oxidation. The results of the determination of the PV are given in Table 3. Freshly refined oils usually have a PV below 1 meq. O_2/kg of oil [5]. The general recommendation identifies oils with a PV lower than 2 meq. O_2/kg oil as oils in good condition. Of the samples analyzed, four refined oils and one CPO belonged to this group, i.e. 28% of the

total. A fat is considered to be rancid at a peroxide value exceeding 10 meq. O_2/kg oil [41]. According to the Codex Alimentarius standards [32], the PV for virgin and cold-pressed fats and oils should not exceed 15 meq. O_2/kg oil, and for other fats and oils 10 meq. O_2/kg oil. None of the samples exceeded these values.

3.5. Oxidative Stability

The Rancimat test is one of the most commonly used methods for predicting the induction period (IP), or the so-called oxidative stability index (OSI) of oil. IP is used to examine the degree of oil needed to resist oxidation at elevated temperatures. Unlike PV, which provides static means of oil stability, IP is a dynamic measurement based on the detection by oxidation-formed volatile acids. IP is able to provide an insight of oil providence during heating and frying. The longer the measured IP, the more stable the oil (see Table 3). A negative linear correlation between the amount of PUFA and the length of the IP was confirmed (Pearson correlation coefficient r = −0.94, $p < 0.05$) for the samples tested. However, there was no linear correlation between α-tocopherol (r = 0.07), total tocopherols (r = 0.06), or α-TE (r = 0.06) and IP. This discrepancy can be explained by the significant dependence of the antioxidant efficacy of tocopherols on experimental conditions and the possible involvement of tocopheroxyl radicals (especially the α-tocopheroxyl radical) in side (pro-oxidant) reactions observed in in vitro systems [42,43]. Thus, a prolonged IP cannot be inferred from the high tocopherol content. For example, sample 12, a cold-pressed oil from organically grown seeds, with the highest content of total tocopherols, α-tocopherol, and α-TE, showed one of the shortest IPs. The average IP of the oils from the traditional varieties was 2.6 h, predisposing them to cold cooking or short-term frying, while the 11.8 h of the four HOSO oils refers to the possibility of long-term heat stress. Both values were consistent with the range of 1–4 h, as published in the literature [44–47]. For comparison, typical IP values in hours are given for palm oil (7–12), soybean oil (1–7), rapeseed oil (3–5), and olive oil (6–11), performed at 120 °C [44].

3.6. Process Contaminants: 3-MCPD, 2-MCPD, and Glycidyl Esters

It is known that during the refining of fats and oils, esters of 3-chloropropane-1,2-diol (3-MCPD), 2-chloropropane-1,3-diol (2-MCPD), and glycidyl esters with fatty acids are formed to a limited extent [48,49]. Generally, they are formed especially in the deodorization step at temperatures above 200 °C. Of these process contaminants, chlorpropanols are considered by the International Agency for Research on Cancer (IARC) to be suspected carcinogens with genotoxic potential, classified as Group 2B, while glycidol is probably carcinogenic to humans and belongs to Group 2A [50]. Therefore, Commission Regulation (EU) No. 2023/915 sets maximum limits for esters of 3-MCPD, with fatty acids expressed as 3-MCPD for selected oils, including sunflower oil, at 1250 µg/kg and for glycidyl esters expressed as glycidol at 1000 µg/kg [51].

Consistent with the fact that the formation of these contaminants is related to temperature stress, they were not detected in any of the CPOs. The deodorization parameters and the concentration of precursors, mainly chlorine donors and partial esters of glycerol, account for the different concentrations of these substances in the refined oils. The concentrations of 3-MCPD esters determined for refined oil samples in the range of <50 to 337 µg/kg and glycidyl esters in the range of <50 to 440 µg/kg met the legislative limits (see Table 4). The concentration of 2-MCPD esters was below the limit of quantification or limit of detection in all samples. According to the literature [52], the ratio of 2-MCPD esters/3-MCPD esters ranges from 0.4 to 0.5 in sunflower oils, which corresponds to the levels determined.

Table 4. Content of 3-MCPD, 2-MCPD, and glycidyl esters with fatty acids in sunflower oils.

Sample No.	3-MCPD Esters [1] [µg/kg]	2- MCPD Esters [1] [µg/kg]	Glycidyl Esters [1] [µg/kg]
1	<LOQ [2]	<LOD [3]	<LOQ
2	<LOQ	<LOD	312 ± 16
3	<LOQ	<LOD	440 ± 22
4	220 ± 11	<LOQ	389 ± 19
5	<LOQ	<LOD	393 ± 20
6	<LOQ	<LOD	354 ± 18
7	<LOQ	<LOD	<LOQ
8	<LOD	<LOD	301 ± 15
9	<LOQ	<LOD	425 ± 21
10	337 ± 17	<LOQ	<LOQ
11	260 ± 13	<LOQ	<LOQ
12	<LOD	<LOD	<LOD
13	170 ± 9	<LOD	436 ± 22
14	<LOD	<LOD	<LOD
15	<LOD	<LOD	<LOD
16	<LOD	<LOD	<LOD
17	<LOQ	<LOD	<LOQ
18	<LOQ	<LOD	175 ± 9

[1] Concentration is expressed as the amount of 3-MCPD, 2-MCPD, and glycidol from the respective esters; [2] LOQ = limit of quantification = 150 µg/kg; [3] LOD = limit of detection = 50 µg/kg. Values are expressed as mean ± standard deviation (SD).

3.7. Sensory Evaluation

During the refining process, most of the undesirable components of the oil are deliberately removed, many of which are sensory active, influencing color (chlorophyll and its degradation products, carotenoids), taste, and odor. Thanks to the long tradition of using refined oils, consumers expect an oil that is light in color and almost neutral in taste and odor. Any volatile substances are therefore considered to be indicative of defects or rancidity. Some oils may exhibit off-flavor defects described as musty, moldy, yeasty, straw-like, roasted, or burnt, indicating improper storage of raw materials, processing, and storage of the oil. In particular, rancid, oily, bitter, leafy, bean-like, or fishy flavors are considered to be signs of rancidity. One of the most important compounds responsible for the perception of rancidity with a very low odor threshold was reported to be (2*E*)-hept-2-enal, the secondary degradation product of linoleic acid [11,53]. Cold-pressed sunflower oils, obtained from good-quality shelled seeds, are characterized by a sunflower-seed or nutty flavor. The volatile profiles of these oils are characterized by terpenic compounds in which α-pinene predominates. Another interesting compound that also contributes to the volatile profile of hazelnuts is 3-methyl-1-butanol (isoamylalcohol), with a pungent and sweet odor [53]. Whole-seed oils have a more pronounced flavor and the additional attributes of being woody, astringent, bitter, or pungent [54]. These attributes are not a defect of these oils provided that they do not interfere with the overall harmony of flavor. The phenolic compounds responsible for the bitter taste were reported more in the seeds, while they were only present in trace amounts in the oils [53].

The sensory profile and the verbal and overall assessment of the samples demonstrated that the oils tested did not have any major organoleptic defects (see Table 5). The modus and the median of overall score was six (excellent), not only for the whole set of 18 oils but also for the separated groups of cold-pressed, refined, traditional, and HOSO oils. Nor did the groups differ by organic or conventional farming methods, and the modus, and the median total score were also six. In line with the literature [53,54], the assessors rated positively the characteristics of sunflower seed-like, nutty, and grainy. All attributes describing rancid flavor, burnt flavor, and bitterness were rated as negative. Interesting and non-standard is the combination of two characteristics of the oils: cold pressing and high oleic acid content, as in samples 15 and 16. The composition of fatty acids makes

them suitable for deep-frying, while the presence of volatiles, not removed by refining, makes them suitable for cold cooking. The latter option is more reasonable, as the sensory active compounds evaporate into the air when CPOs are heated and are transferred to fried products, where their presence is usually perceived by consumers as disturbing.

Table 5. Sensory evaluation of sunflower oils.

Sample No.	Odor Pleasantness	Taste Pleasantness	Pungent Intensity	Off-Flavor Intensity	Overall Rating (Median)	Overall Rating (Modus)	Verbal Assessment
1	76 ^{bc}	82 ^{a}	2 ^{a}	3 ^{a}	5.5	6	Neutral-tasting oil with only a very subtle nutty flavor
2	63 ^{bc}	65 ^{ab}	11 ^{b}	9 ^{a}	5	5	Oil with a mild taste of the raw material, with a very slight pungency
3	79 ^{b}	89 ^{a}	2 ^{a}	2 ^{a}	6	6	Oil of lighter color, completely neutral taste, without aftertaste
4	53 ^{d}	67 ^{ab}	10 ^{b}	15 ^{b}	4.5	5	Oil with a slight taste of the raw material, very slightly spicy
5	71 ^{bc}	54 ^{b}	4 ^{a}	10 ^{ab}	3.5	4	Stronger oily taste, with a slight roasted taste
6	67 ^{cd}	67 ^{ab}	3 ^{a}	4 ^{a}	5	5	Oil of nearly neutral taste, with only a very slight nutty flavor
7	59 ^{cd}	56 ^{ab}	13 ^{b}	12 ^{ab}	4.5	5	Stronger oily taste, with a slight bitterness and spiciness in the aftertaste
8	62 ^{d}	74 ^{ab}	4 ^{a}	7 ^{a}	6	6	Neutral-tasting oil without any off flavors
9	80 ^{b}	87 ^{a}	4 ^{a}	4 ^{a}	6.5	6	Neutral-tasting oil without any off flavors
10	53 ^{d}	61 ^{ab}	21 ^{c}	13 ^{b}	4	4	Slight pungency in taste
11	72 ^{bc}	84 ^{a}	2 ^{a}	5 ^{a}	6	6	Neutral-tasting oil without any off flavors
12	90 ^{a}	83 ^{a}	7 ^{ab}	5 ^{a}	6	6	Distinctive flavor after sunflower seeds and nuts
13	76 ^{bc}	82 ^{a}	3 ^{a}	3 ^{a}	5.5	6	Oil with an almost neutral taste
14	89 ^{ab}	78 ^{ab}	8 ^{ab}	4 ^{a}	6	6	Distinctive flavor after sunflower seeds and nuts
15	56 ^{cd}	48 ^{b}	11 ^{b}	20 ^{b}	4.5	4	Slightly bitter in taste, distinctive flavor after seeds, nuts, straw
16	78 ^{b}	79 ^{a}	12 ^{b}	4 ^{a}	6	6	Strong flavor after sunflower seeds, nuts, with a slight spicy aftertaste
17	92 ^{a}	88 ^{a}	1 ^{a}	1 ^{a}	6.5	7	An exceptional oil with a completely neutral taste
18	87 ^{ab}	86 ^{a}	2 ^{a}	2 ^{a}	6	6	Neutral-tasting oil without any off flavors

$^{a–d}$ Values marked with different letters in the same column indicate a statistically significant difference by one-way analysis of variance with Scheffe's post hoc test ($p < 0.05$). Scale orientation: pleasantness 0 = extreme dislike, 100 = extreme like; intensity 0 = not noticeable, 100 = very strong sensation, overall rating scale: 1—very poor, 2—poor, 3—fair, 4—good, 5—very good, 6—excellent, 7—exceptional.

4. Conclusions

The study demonstrated that the current sunflower oils on the Central European market are of high quality. The 18 monitored oils generally met the recommended analytical parameters and the limits set by legislation with a significant reserve. The oils tested did not have any major organoleptic defects and the overall sensory quality was assessed on a scale from good to exceptional. The nutritional benefit of all types of sunflower oils was found to be the high content of vitamin E, especially α-tocopherol. However, it should be recognized that sunflower oils are not a significant source of omega-3 fatty acids. New types of oils, obtained by targeted breeding of annual sunflower varieties, have extended their utility value. From these new varieties, just high oleic sunflower oil (HOSO), whose characteristic very high oxidative stability has been confirmed, is widely commercially available. This makes the oil particularly suitable for long-term heat stress during deep frying. Cold-pressed oils, on the other hand, have the advantage of delicate taste and smell similar to sunflower seeds and nuts.

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