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Physicochemical Properties and Sensory Attributes of Cold-Pressed Camelina Oils from the Polish Retail Market

Monika Momot [1,2], Barbara Stawicka [2] and Aleksandra Szydłowska-Czerniak [1,*]

[1] Department of Analytical Chemistry and Applied Spectroscopy, Faculty of Chemistry, Nicolaus Copernicus University in Toruń, Gagarina 7, 87-100 Toruń, Poland
[2] Bunge Polska Sp. z o.o., Niepodległości 42, 88-150 Kruszwica, Poland
* Correspondence: olasz@umk.pl; Tel.: +48-56-611-4786

Abstract: Cold-pressed camelina oil (CPCO) is exceptional seed oil with a unique fatty acid profile promoting health and wellness. Therefore, this work focused on estimating and comparing the physicochemical properties and sensory quality of eight CPCO samples available on the Polish market. All analyzed oils were rich in α-linolenic acid (ALA = 29.91–36.27%) and contained low amounts of saturated fatty acids (SAFA = 10.61–12.20%). Oxidative stability of the studied CPCO samples, using the Rancimat test, ranged between 4.8 and 6.8 h, while peroxide (PV = 0.58–4.61 meq O_2/kg) and anisidine (AnV = 0.15–1.60) values differed significantly. Moreover, the water and volatile matter contents (WVMC = 0.05–0.17%) and phosphorus level (P = 3.03–13.58 mg/kg) were monitored in commercial CPCO samples. Low concentrations of polycyclic aromatic hydrocarbon contaminants (Σ4PAHs = 0.72–7.22 µg/kg) were established in all oils. A quantitative descriptive analysis (QDA) was developed to characterize the sensory properties of eight CPCO samples. Six oil samples had high overall sensory quality (OSQ > 4.0), but OSQ < 3.5 was an unacceptance sensory quality for two of the oils. The developed lexicon might be used in the oil industry to monitor product quality, sensory profiling of new product development, and benchmark competitors' samples.

Keywords: cold-pressed camelina oils; fatty acid profile; oxidative stability; polycyclic aromatic hydrocarbons; sensory quality; quantitative descriptive analysis; chemometric analysis

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1. Introduction

Camelina sativa (L.) Crantz, as an important oilseed crop belonging to the family of *Cruciferae* (*Brassicaceae*), is cultivated for oil in Europe, North America, and Central Asia. Camelina, known as gold-of-pleasure, false flax, wild flax, linseed dodder, German sesame, and Siberian oilseed, is a new oilseed with a promising future as a food product due to its high amounts of unsaturated fatty acids and bioactive compounds with health-promoting effects [1]. Camelina oil can be extracted from whole and crushed seeds using cold or warm pressing, solvent extraction with hexane, supercritical carbon dioxide, and an enzyme or ultrasound-assisted extraction [2–4]. Among the known techniques of camelina oil extraction, cold pressing can be considered safe, more natural, environmentally friendly, and requires less energy. Conventionally, most camelina seed oil extraction is done with a cold press process. Whole or crushed camelina seeds are pressed at room temperature with a cold-pressing machine. However, pressure applied in screw presses on the seeds can increase the temperature to upper 60 °C. Therefore, sometimes cold pressing requires an additional cooling system to keep the specified limit temperature. Double mechanical pressing of camelina seeds is a common practice due to their high oil content. The obtained cold-pressed oil can be physically purified through filtration, sedimentation, or centrifugation processes. Nevertheless, many factors, such as camelina seed varieties, amounts of oil and water in seeds, technical parameters of the screw-press machine (rotational speed, nozzle diameter, barrel spacing, operating pressure, feed rate),

temperature (hot or cold), and seed pretreatment affected the efficacy of camelina oil recovery by mechanical pressing [2–4].

Camelina oils recovered from *Camelina sativa* seeds have low amounts of saturated fatty acids (SAFA = 2.5–18.45%, mainly palmitic acid), medium monounsaturated fatty acids (MUFA = 12.3–49.3%), and high levels of polyunsaturated fatty acids (PUFA = 32.4–58.5%). Interestingly, camelina oils are a rich source of α-linolenic acid (ALA), with a content ranging between 12.0% and 44.3% [2]. ALA is an essential omega-3 (n-3) fatty acid to humans because it cannot be synthesized in the body, playing a supportive role in the cardiovascular and immune human system [5].

The differences in the amounts of ALA, other fatty acids, and quality parameters of oils cold pressed from *Camelina sativa* seeds were influenced by factors such as climatic and growing conditions, genotype diversity, seed storage, technological processes, and analytical methods [6–10]. Consequently, the high content of unsaturated fatty acids in camelina oils decreases their oxidative stability. For this reason, camelina oil is more susceptible to oxidation than rapeseed oil but more stable than linseed oil, which is richer in PUFA [11,12].

However, camelina oil is generally considered a high-quality vegetable oil for its health-promoting bioactive components, including tocopherols, polyphenols, carotenoids, catechins, phytosterols, saponins, and squalene [1,4,7,9,10,13,14]. Potent antioxidants, especially tocopherols and phenolic compounds, make camelina oils more stable for oxidation reactions than other highly unsaturated vegetable oils such as linseed and fish.

Despite the desirable health aspects of bioactive compounds and PUFA present in camelina oils, they can be contaminated with toxic compounds, such as polycyclic aromatic hydrocarbons (PAHs), pesticides, and mycotoxins [15]. On the other hand, many factors, such as environmental pollution during *Camelina sativa* seed growth, contamination during the harvesting, and technological processes, can significantly contribute to increasing the levels of these undesirable compounds. There are two main sources of PAH contaminations in camelina oils: (1) the contact of seeds with polluted surroundings and (2) the drying process of seeds before oil pressing by direct contact with combustion gases. Among PAHs, benzo(a)pyrene (B(a)P) is classified as carcinogenic to humans and often has been used as a marker. The maximum concentration of B(a)P in vegetable oils based on the European Commission Regulation No 835/2011 [16] is 2 μg/kg. However, B(a)P is not a sufficient indicator of the PAHs content; thus, four PAHs (∑4PAHs) such as B(a)P, benzo(a)anthracene (B(a)A), benzo(b)fluoranthene (B(b)F), and chrysene (Chr) have been defined for better indicate oil contamination with PAHs. The maximum acceptance value for ∑4PAHs in vegetable oils is 10 μg/kg [16].

It is known that the high amounts of unsaturated fatty acids in camelina oils during free-radical chain reactions in the presence of oxygen can form oxidation products, which are responsible for oxidative rancidity, discoloration, and poor nutritional and sensory characteristics. The breeding region and storage conditions (time, type of packaging, temperature, exposure to daylight) significantly affected the oxidative stability and quality parameters of various camelina oils [1,8–10,17]. Moreover, free fatty acid (FFA) content indicating the degree of hydrolytic changes evaluated based on the acid value (AV) and amounts of moisture and phospholipids, are critical parameters of interest because they determine the shelf-life quality and hence the economic value of camelina oils.

An evaluation of the chemical compositions of oils cold-pressed from *Camelina sativa* seeds can deliver valuable information about their quality. However, the use of chemical composition only is not adequate to predict the sensory profile and complex oil quality. The combination of the chemical and sensory data is of critical importance for estimating the interaction between various compounds. On the other hand, the flavor and taste of cold-pressed oils depend on the growing seed regions, environmental conditions, variety and ripeness degree of seeds, storage time and conditions, processing conditions, and oxidation degradation of oils [18–22].

In general, considerable amounts of volatile compounds, mainly unsaturated aldehydes, can originate from autooxidation reactions of unsaturated fatty acids in cold-pressed oils [23]. Therefore, the high concentration of ALA in oils cold-pressed from *Camelina sativa* seeds induces high susceptibility to undesirable autooxidation processes resulting in unpleasant odor constituents. In contrast, this oil had an attractive yellow color and mustard-like taste [3]. Moreover, the deodorization process at a temperature above 225 °C affected the odor and flavor deterioration of camelina oils due to the formation of aldehydes, ketones, and alcohols contributing to the sensory quality [18]. Negative odor attributes, such as metallic (1–3 scores), mineral (1–3 scores), or plastic (2–3 scores), appeared. However, the positive attributes of crude camelina oil, such as green/grassy (0–1 scores) for odor and green leaves (0–2 scores) for flavor, were also evaluated [18]. Additionally, the most intense leafy (2.5 scores), herbal (2.4 scores), and hay (1.8 scores) odor and aroma was detected for the camelina seed oil available at retail in Slovenia [22]. On the other hand, quality scores for the appearance (8.7–9.2) and aroma (7.2–8.7) of camelina oil-based spread did not change significantly during storage for 16 weeks at 4 and 8 °C, whereas flavor (6.8–8.3) and overall quality (7.3–8.7) scores were insignificant lower for the camelina spread from 6–14 weeks [24].

However, to our knowledge, information on the sensory characteristics of oils cold-pressed from *Camelina sativa* seeds is scarce. Neither the American Oil Chemists' Society (AOCS) standard nor the German Society for Fat Science (DGF) standard does not describe the sensory attributes of these oils. Nevertheless, sensory analysis remains an essential tool for assessing oil quality. Quantitative descriptive analysis (QDA) is one of the most extensively used sensory methods to profile a product in all its sensory characteristics and differentiation of various food matrices. The QDA is a highly detailed and valid method widely used in many food products to quantify each attribute of a product. The attributes that define and/or characterize the food are determined, and their quantitative importance in terms of intensity is assigned. This method yields consistently good results in sensory food evaluation, and it is notable for its reliability and precision due to a trained panel being required. For this reason, QDA was developed to characterize and compare the sensory quality of different cold-pressed edible oils, such as sunflower oil, rapeseed oil, their blends fortified with oil from chia and sesame seeds, safflower oil, lemon seed oil, and other unconventional oils and fats [20–22,25,26].

However, there is no data about applying the QDA to design a sensory profile for cold-pressed camelina oil (CPCO) available at Polish retail.

Therefore, this study explored and compared the physicochemical and sensory characteristics of commercially available CPCO samples to define their overall quality. Moreover, QDA methodology was applied for the first time to find the sensorial descriptors necessary to explain the desirable sensory attributes of the investigated oils. The created descriptive lexicons can be used to characterize the sensory quality (define the sensory attributes precisely, corresponding definition and intensity of descriptors) of the studied oils. In addition, chemometric methods such as principal component analysis (PCA) and hierarchical cluster analysis (HCA) were used for grouping the analyzed CPCO samples and the physicochemical and sensory parameters, their characterization, and detection of differences.

2. Materials and Methods

2.1. Reagents and Samples

All chemicals and solvents used in the experiments were supplied by Merck Sp. z o. o. (Warszawa, Poland).

The eight CPCO samples were produced by the most popular Polish manufacturers and purchased in the original packaging during their shelf life on the Polish market. The oils were named in the order in which they were obtained, from CPCO1 to CPCO8, and stored in dark brown glass bottles of 250 mL (CPCO1), 500 mL (CPCO2, CPCO3, CPCO4, CPCO5, CPCO8), 200 mL (CPCO6), and 100 mL (CPCO7) at 4 °C until analysis.

2.2. Determination of Physiochemical Parameters of Cold-Pressed Camelina Oils

2.2.1. Fatty Acid Profile

The fatty acid composition of each CPCO was analyzed based on the ISO 5508:1996 official method [27]. By following the ISO 5509:2000 [28] standard method, fatty acid methyl esters were analyzed using a gas chromatograph (HP 5890 GC) fitted with a capillary column BPX 70 (60 m × 0.25 mm, 0.25 µm) and equipped with a flame-ionization detector (FID) (Hewlett-Packard, Avondale, PA, USA). The initial furnace temperature was 150 °C and was increased to 210 °C at 1.3 °C/min. The temperature of 210 °C was maintained for 5 min, while the temperature of the injector and detector was set at 250 °C. Helium at a flow rate of 0.6 mL/min was used as the carrier gas. The individual peaks were identified by comparing their retention times with the standard of fatty acid methyl esters. The concentrations of individual fatty acids were expressed in percent of total fatty acids. All results are based on triplicate analysis.

2.2.2. Characteristic Values

Peroxide value (PV), anisidine value (AnV), and free fatty acids (FFA) of the analyzed CPCO samples were measured in triplicate based on the official methods described by ISO 27107:2010 [29], ISO 6885:2016 [30], and ISO 660:1996 [31], respectively.

The PV was determined potentiometrically after dissolving the oil in the chloroform-acetic acid mixture with a saturated solution of potassium iodide by titration with sodium thiosulfate using an automatic titrator (905 Titrando, Metrohm, Warszawa, Poland). The PV expressed as milliequivalents of O_2/kg oil was calculated according to the following equation:

$$\mathrm{PV}\ (\mathrm{meq}\ \mathrm{O_2/kg}) = \frac{(\mathrm{V} - \mathrm{V_b}) \times \mathrm{c} \times 1000}{\mathrm{m}}$$

where V and V_b are the volumes of used sodium thiosulfate by oil sample and blank, respectively (mL), c is the concentration of sodium thiosulfate (mol/L), and m is the oil weight (g) [29].

The AnV was measured spectrophotometrically before and after the reaction of the dissolved oil in isooctane with a p-anisidine reagent. The absorbance measurement of each reaction mixture in a 1 cm quartz cell was carried out at 350 nm using a Hitachi U-2900 spectrophotometer (Hitachi, Tokyo, Japan) [30]. This is a measure of the number of aldehydes present in the studied oil.

The FFA content (acidity) is a parameter used to evaluate oil quality, reflecting the extent of hydrolytic activities. This measurement is based on the direct titration of an oil sample in an alcoholic medium with a standard potassium hydroxide solution using phenolphthalein as the indicator. This procedure measures the number of free acid groups existing in the studied oil systems. The FFA content expressed as a percentage mass fraction was calculated by the following formula:

$$\mathrm{FFA}\ (\%) = \frac{\mathrm{V} \times \mathrm{c} \times \mathrm{M} \times 100}{1000 \times \mathrm{m}}$$

where V is the volume of potassium hydroxide solution used for titration (mL), c is potassium hydroxide concentration (mol/L), M is the molar mass of the oleic acid (g/mol), and m is the oil weight (g) [31].

2.2.3. Oxidative Stability

The oxidative stability of CPCO samples was analyzed with 743 Rancimat apparatus (Metrohm, Herisau, Switzerland) according to the AOCS Official Method Cd 12b-92 [32]. Briefly, each CPCO was weighed (3.00 ± 0.01 g) and oxidized by an airflow of 20 L/h at 100 ± 0.3 °C in a measuring cell supplied with distilled water. The induction period (IP) was determined by measuring the conductivity of the distilled water with collected volatile

oxidation products. This experiment was carried out in triplicate for each oil, and the IP was expressed in hours (h).

2.2.4. Water and Volatile Matter Contents

The water amount and volatile matter content (WVMC) in the analyzed CPCO samples were determined in triplicate by drying 10 g of each oil in an oven at 103 °C according to ISO 662:2016 [33]. These measurements were repeated each hour by removing and weighing the mixtures until the weight was constant.

2.2.5. Phosphorus Content

The content of phosphorus (P) was measured by inductively coupled plasma optical emission spectrometry using an ICP-OES Optima 8300 Perkin Elmer spectrometer (Waltham, MA, USA), according to ISO 10540-3:2012 [34]. In brief, each oil sample was diluted with V-solvent (1:5, Perkin Elmer) to reduce the oil's viscosity for better nebulization. The ICP-OES parameters for the P determination were as follows: generator power—1500 W, gas type—argon, outer gas—15 L/min, intermediate gas—1 L/min, nebulizer gas—0.5 L/min, nebulizer pressure—3.1 bar, sample uptake rate—1.5 mL/min. P was detected at the major emission lines of 213.620 and 214.915 nm. Three replications for each sample were performed.

2.2.6. Polycyclic Aromatic Hydrocarbons Content

Each CPCO was dissolved in cyclohexane and extracted to dimethyl formaldehyde. The determination of four PAHs (B(a)P, Chry, B(a)A, and B(b)F) in the studied oil samples was carried out with the high-performance liquid chromatography with the fluorescence detector (HPLC-FLD, Shimadzu, Kyoto, Japan). OpenLAB CDS ChemStation Edition Software version 10.1 (Agilent Technologies, Waldbronn, Germany) was used for data acquisition and analysis. The reversed-phase column used for the PAHs analysis was a Zorbax Eclipse PAH column (particle size 3.5 µm, length 150 mm, diameter 4.6 mm, Agilent, Santa Clara, CA, USA) with a precolumn Eclipse XDB-C18 (3.5 µm, 4.6 × 150 mm, Agilent) at an oven temperature of 30 °C. Benzo(b)chrysene was used as an internal standard. PAH standards were diluted into acetonitrile, and calibration curves were prepared using the peak areas as a function of the PAH concentration standards (0.25–8.50 µg/kg). The PAHs analysis was repeated three times for each oil sample.

2.3. Sensory Analysis of Cold-Pressed Camelina Oils

2.3.1. Sensory Profiling

QDA was employed to describe the sensory characteristic of the CPCO samples according to ISO 13299:2016 [35]. The sensory training was performed by 10 well-selected panelists (eight females and two males, ages 25–42) according to ISO 8586-1:1996 [36]. Assessors were selected, trained, and monitored according to guidelines in this international standard [36]. Selected assessors are chosen for their ability to perform a sensory test. They were asked to identify basic tastes described in ISO 3972 (2011) [37] and participated in the odor recognition test based on ISO 5496 (2006) [38]. Before participating in the sensory analysis, the assessor had gained tremendous experience and knowledge of sensory descriptors for oils and fats products. Moreover, sensory training about specific attributes present in CPCO was conducted before assessments. Panelist training was divided into three phases: (1) lections generation (5 sessions), (2) training on attributes recognition and understanding definition (15 sessions), and (3) panel performance checking (3 sessions). During the first phase, elections of oils pressed from *Camelina sativa* seeds were developed by presenting 10 commercial CPCO samples collected from the marketplace. The sensory lexicon of CPCO, including nine attributes, was developed: one taste attribute (bitter), six flavor attributes (overall flavor intensity (OFI), cabbage-like, nutty-like, mustard-like, fruity-like, woody-like), and two attributes of mouth feeling category (astringency and

persistence). Descriptors for CPCO, their definitions, and the used reference standards are presented in Table 1.

Table 1. Sensory descriptive vocabulary for quantitative descriptive analysis of cold-pressed camelina oils.

Sensory Attributes	Definition	Reference Product	Score
Overall flavor intensity (OFI)	The overall strength of all flavor and taste attributes	Freshly refined rapeseed oil—1, Cold-pressed black cumin oil—8	1; 8
Bitter taste	The basic taste elicited by quinine and caffeine	Caffeine in water (0.2%) or extra virgin olive oil (high quality)	7
Cabbage-like flavor	Flavor associated with asparagus, cabbage or fresh green vegetables	Fresh cold-pressed camelina oil	4–5
Nutty-like flavor	The flavor associated with fresh nuts	Fresh cold-pressed peanut oil	10
Mustard-like flavor	The flavor associated with mustard, onion, spicy	Fresh cold-pressed camelina oil	5–6
Fruity-like flavor	The flavor associated with ripe fruit	Extra virgin olive oil	10
Woody-like flavor	The flavor associated with fresh, dry, cut wood	Stored cold-pressed camelina or rapeseed oil for 18 months	8.5
Astringency	The shrinking or drying effect on the tongue surface elicited by tannins	Slices of a green banana	10
Persistence	How long do flavor sensations remain aftertaste	Refined camelina oil—0, Cold-pressed linseed oil or cold-pressed black cumin oil stored for 5 months—10	0; 10

During the second training phase, panelists were trained to recognize and quantify the intensity of each attribute with an intensity rating scale from 0–10, where 0—attribute not detected and 10—attribute extremely strong. Reference samples for each attribute listed in Table 1 were presented to the panelist and were crucial for the achievement of consensus regards to the definition. Some reference samples were taken from the ASTM E1627-94:2004 [39] for sensory evaluation of edible oils and fats. Phase 2 was successfully finished when a consensus among panelists was reached. During the last phase, the performance panel was checked (repeatability, reproducibility, discrimination), and only the assessors who showed good repeatability of the results were selected.

2.3.2. Sensory Quality

Additionally, the overall sensory quality (OSQ) of studied CPCO samples was evaluated at the sum of all indicated attributes, their compatibility, and harmonization. To determine the OSQ of each CPCO, the 5-point quality scale was developed (Table 2), starting from "very bad sensory quality—1" to "excellent sensory quality—5" based on the available methods: DGF-C II 1, 09:2009 [40] and AOCS Cg 2-83 [41].

Table 2. Overall sensory quality. General characteristic of cold-pressed camelina oils.

Score	Quality Level	Characteristic
5	Very good	Extra good taste characteristic for cold-pressed camelina oil with positive attributes such as mustard-like, cabbage-like at medium/ high intensity, slightly fruity-like and nutty-like flavor.
4	Good	Good taste, positive flavor such as mustard-like, cabbage-like at medium intensity. Slightly bitter and woody-like at low-intensity acceptance.
3	Fair	Negative taste attributes such as bitter and woody-like flavor and mouth feeling attributes such as astringency and persistence at low intensity were identified.
2	Bad	Negative taste attributes such as bitter and woody-like flavor and mouth feeling attributes such as astringency and persistence at moderate intensity were identified.
1	Very bad	Negative taste attributes such as bitter and woody-like flavor and mouth feeling attributes such as astringency and persistence at high/very high intensity were identified.

In the available standards (AOCS and DGD) and the literature, there is no information about typical and atypical characteristics of cold-pressed oil from *Camelina sativa* seeds.

Industrial laboratories often use the quality scale to assess the products' OSQ. According to this methodology, fresh oil products should have at least good quality to be sure that oils at the end of shelf life will still have acceptable quality for consumers. Sensory quality is unacceptable, and the product cannot be released on the market after a score below 4.0 for the fresh oil.

2.3.3. Tasting Methodology

Eight CPCO samples were evaluated by a 10-well-trained sensory panel. Ten assessors were asked to analyze oil samples prepared monadically using a 0–10 cm scale and to determine OSQ using a 5-pointing scale.

For the sensory session, 80 mL of each oil was kept at room temperature in a transparent glass jar with a lid (150 mL). All oil samples were coded with three-digit code numbers and presented in a randomized order to the assessors. Before tasting, the panelists were instructed to rinse their mouths with weak, warm black tea or eat an apple slice to clean their palate. The sensory sessions were carried out at sensory booths in Sensory Laboratory, fulfilling the requirements of ISO 8589:2007 [42]. Assessors were assigned to the individual sensory booths, and throughout sensory evaluation, the temperature (22.0 $\pm$ 2 °C) and humidity (45%) were controlled. Each booth was equipped with appropriate lighting and a computer with Fizz Biosystems Software to save the sensory data analysis. Sensory sessions were conducted in three repetitions by ten assessors.

2.4. Statistical Methods

All physicochemical measurements were conducted in triplicate and reported as means $\pm$ standard deviation (SD).

One-way ANOVA, followed by the Duncan test, was performed to analyze the significant differences between physicochemical and sensory data ($p < 0.05$).

The scores and loadings of the sensory data analyzed by PCA were displayed as a bi-plot. HCA with Ward's method using Euclidean distances was applied to identify CPCO samples based on the degree of similarity among physicochemical parameters and sensory quality.

A correlation matrix was constructed to evaluate relationships between the physicochemical parameters and sensory quality of analyzed oils, using Pearson correlation coefficients (r).

Statistical analyses were conducted using Statistica (Windows software package, version 8.0; StatSoft Inc., Tulsa, 274 OK, USA), while Fizz Biosystems software (Biosystems, Courtenon, France) was applied for the collection of all sensory data.

3. Results and Discussion

3.1. Fatty Acid Compositions of Cold-Pressed Camelina Oils

The determination of fatty acids in edible oils is crucial for oil quality from a nutritional standpoint and lipid oxidation products. Moreover, the fatty acid composition is an important feature for authentication purposes.

As can be seen in Table 3, all studied oil samples presented a typical fatty acid profile within the recommended limits for CPCO specified in the Codex Alimentarius [43].

Table 3. Main fatty acids of the cold-pressed camelina oils.

Fatty Acid	Content * ± SD (%)							
	CPCO1	CPCO2	CPCO3	CPCO4	CPCO5	CPCO6	CPCO7	CPCO8
C16:0	5.24 ± 0.08 ^{b}	5.70 ± 0.01 ^{d}	6.46 ± 0.01 ^{f}	6.56 ± 0.01 ^{g}	5.71 ± 0.01 ^{d}	5.74 ± 0.01 ^{e}	5.59 ± 0.01 ^{c}	5.00 ± 0.00 ^{a}
C18:0	2.34 ± 0.01 ^{a}	2.75 ± 0.03 ^{b}	2.66 ± 0.02 ^{c}	2.63 ± 0.04 ^{c}	2.41 ± 0.02 ^{b}	2.63 ± 0.01 ^{c}	2.34 ± 0.01 ^{a}	2.65 ± 0.01 ^{c}
C20:0	1.67 ± 0.06 ^{d}	1.40 ± 0.04 ^{a}	1.75 ± 0.03 ^{d,e}	1.69 ± 0.05 ^{d}	1.58 ± 0.02 ^{c}	1.47 ± 0.02 ^{a,b}	1.52 ± 0.05 ^{b,c}	1.82 ± 0.07 ^{e}
C22:0	1.50 ± 0.03 ^{d}	1.65 ± 0.03 ^{e}	1.05 ± 0.03 ^{b}	1.05 ± 0.03 ^{b}	1.33 ± 0.03 ^{c}	1.55 ± 0.01 ^{d}	1.52 ± 0.03 ^{d}	0.93 ± 0.04 ^{a}
∑SAFA	10.75	11.50	11.92	11.93	11.03	11.39	10.97	10.40
C18:1	17.97 ± 0.03 ^{e}	15.71 ± 0.05 ^{a}	18.52 ± 0.06 ^{g}	18.33 ± 0.06 ^{f}	17.26 ± 0.03 ^{d}	16.46 ± 0.01 ^{c}	15.86 ± 0.03 ^{b}	20.47 ± 0.02 ^{h}
C20:1	16.87 ± 0.03 ^{e}	16.05 ± 0.03 ^{d}	14.16 ± 0.03 ^{b}	13.84 ± 0.15 ^{a}	15.99 ± 0.01 ^{d}	16.04 ± 0.05 ^{d}	15.62 ± 0.04 ^{c}	16.01 ± 0.22 ^{d}
C 22:1	2.91 ± 0.03 ^{a}	3.06 ± 0.01 ^{b}	2.95 ± 0.02 ^{a}	2.87 ± 0.02 ^{a}	3.36 ± 0.02 ^{c}	3.09 ± 0.04 ^{b}	3.40 ± 0.14 ^{c}	2.95 ± 0.00 ^{a}
∑MUFA	37.75	34.82	35.63	35.04	36.61	35.59	34.88	39.43
C18:2	19.26 ± 0.03 ^{d}	17.15 ± 0.04 ^{a}	21.34 ± 0.01 ^{g}	21.92 ± 0.02 ^{h}	19.44 ± 0.04 ^{e}	18.36 ± 0.02 ^{c}	18.20 ± 0.00 ^{b}	19.96 ± 0.03 ^{f}
C18:3	32.27 ± 0.03 ^{d}	36.27 ± 0.03 ^{h}	30.81 ± 0.03 ^{c}	30.69 ± 0.05 ^{b}	32.68 ± 0.02 ^{e}	34.43 ± 0.02 ^{f}	35.59 ± 0.04 ^{g}	29.91 ± 0.05 ^{a}
∑PUFA	51.53	53.42	52.15	52.61	52.12	52.79	53.79	49.87
n-6:n-3	0.60	0.47	0.69	0.71	0.59	0.53	0.51	0.67

* n = 3; SD—standard deviation; different letters ($^{a–h}$) within the same row indicate significant differences between the percentages of fatty acids of cold-pressed camelina oils (one-way ANOVA and Duncan test $p < 0.05$).

All studied CPCO samples are mostly unsaturated (> 80%), being the major fatty acids those of the C18 series: oleic acid (C18:1 = 15.71–20.47%), linoleic (C18:2 = 17.15–21.92%), and linolenic acid (C18:3 = 29.91–36.27%). The Duncan test indicated that the amounts of these three fatty acids in the commercially available CPCO samples differed significantly (Table 3). Thus, linolenic acid was the most abundant in the studied oils, which was similar to the previous reports [1,2,9,10,14,17,44,45].

It is known that linolenic acid (ALA) contributes to the prevention of cardiovascular diseases [5]. Moreover, this fatty acid belongs to the n-3 acids family, which is necessary to maintain the proper function of the body. Essential fatty acids, like ALA, are components of cellular membranes responsible for brain and nervous system function. ALA must be delivered with the daily diet as the human body cannot produce it. Nevertheless, the improper proportion of n-6 to n-3 in food intake in the human diet can develop inflammation and chronic diseases as these acids compete for the same enzymes in the metabolic pathway. It is desirable to lower the amount of n-6 fatty acids in the diet and increase the dietary intake of n-3 fatty acids to reduce the risk of chronic diseases. The varying n-6:n-3 ratios from 1:1 to 5:1 are capable of preventing many non-communicable diseases, which are major health problems worldwide [46]. Although, human nutrition health professionals recommend food products containing an n-6:n-3 ratio closer to 1:1, which reflects the composition of the diet of human ancestors. However, a lower ratio of n-6:n-3 fatty acids had a therapeutic effect on cancer, inflammatory, cardiovascular, and autoimmune diseases [46].

It is noteworthy that the studied commercial CPCO samples are deficient in n-6 PUFA and contain excessive amounts of n-3 PUFA, resulting in a somewhat lower n-6:n-3 ratio ranging from 0.47 and 0.71 (Table 3). Therefore, the n-6:n-3 ratio of about 1:2 in camelina oil is unique among vegetable oils and is beneficial to health. Consequently, each CPCO is rich in n-3 fatty acids, mainly ALA, which gets converted into eicosapentaenoic acid and docosahexaenoic acid. Similar nutritional values in terms of the n-6:n-3 ratio (0.41–0.69) were found in camelina oils by other authors [1,9,12,17,44,45].

Among unsaturated long-chain unsaturated fatty acids, eicosenoic acid (C20:1) was predominantly found in the analyzed oils, having percentages of 13.84–16.87% (Table 3). In contrast, CPCO samples presented similar and low erucic acid (C22:1) content with 2.87–3.40%. The total levels of MUFA and PUFA contained in CPCO samples available on the Polish market were high and varied from 34.82–39.43% and 49.87–53.79%, respectively.

In the case of SAFA, amounts of palmitic acid (C16:0 = 5.00–6.56%) and stearic acid (C18:0 = 2.34–2.75%) in the studied oils were higher than eicosanoic acid (C20:0 = 1.40–1.82%) and docosanoic acid (C22:0 = 0.93–1.65%) presented in smaller amounts (Table 3). Therefore, total SAFA concentrations (10.40–11.93%) in the investigated CPCO samples were approximately three and five times lower than levels of MUFA and PUFA, respectively. The SAFA

results again compared well with corresponding literature values of 7.40–10.53% in various camelina oils [1,9,12,17,44,45].

Significant differences in fatty acid profiles of CPCO samples and the quantities of the fatty acids were observed (Duncan test, Table 3). This can be explained by the fact that the fatty acid compositions of oils available for retail are probably dependent on the varieties of *Camelina sativa* seeds (genetic factors), the growing conditions (climate, soil, and ecological factors), and harvest time.

CPCO, due to its unusual health and wellness-promoting fatty acid composition with high concentrations of unsaturated fatty acids (C18:3, C18:2, C18:1, and C20:1) and desirable low n-6:n-3 ratio, should be of interest for producers and consumers, who are increasingly searching of products with high-quality features. Hence, CPCO consumption can be an important dietary factor in decreasing the n-6:n-3 ratio, which could reduce the development of many chronic diseases.

3.2. Physicochemical Characteristics of Cold-Pressed Camelina Oils

3.2.1. Oxidative Status and Stability

It is well known that the fatty acid profile is a crucial factor responsible for the cold-pressed oil's oxidative stability, which directly affects its overall quality. Due to the content of unsaturated fatty acids in CPCO samples being up to 80% (Table 3), these oils can be prone to oxidation during storage. Nevertheless, the other parameters can be taken under consideration to assess the state of oil deterioration, namely PV, AnV, and FFA. The PV is an indicator of the level of peroxides, which are intermediate products of oil oxidation. However, AnV measures the breakdown products of peroxides such as hydrocarbons, aldehydes, ketones, alcohols, esters, and acids, which cause the appearance of off-flavors and off-odors. Moreover, FFA produced by the hydrolysis of triacylglycerol is a widely used indicator of oil degradation.

Significant differences in PV, AnV, and FFA results were observed between eight commercial CPCO samples (Duncan test, Table 4). However, the highest levels of peroxides (PV = 3.37 and 4.61 meq O_2/kg) were determined in CPCO5 and CPCO1 samples, while these oils had the lowest content of secondary oxidation products (AnV = 0.15 and 0.25, respectively). The formation of lipid peroxide molecules (PV = 1.07–1.12 meq O_2/kg) was similar in CPCO2, CPCO3, and CPCO4. Consequently, AnV data for CPCO1, CPCO3, CPCO4, and CPCO8, as well as CPCO2 and CPCO6, ranged between 0.25–0.34 and 1.58–1.60, respectively. Therefore, the development of rancidity in these oil samples did not differ significantly. On the other hand, the production of FFA in all commercial CPCO samples was low and varied from 0.42–0.98%, which is associated with better oil quality. Generally, oils with low amounts of peroxides (PV = 0.58 and 0.96 meq O_2/kg for CPCO7 and CPCO8) had low FFA concentrations (0.42–0.56%). In contrast, the highest FFA (0.98%) was found in CPCO5, with high content of primary oxidation products (PV = 3.37 meq O_2/kg). Therefore, a prooxidant effect of FFA was observed independently of oils' hydrolytic and oxidative alteration states. The oxidation of triacylglycerols probably leads to the formation of carboxylic acids that possess a glycerol backbone, which is calculated as acidity. Unexpectedly, lower amounts of FFA (0.64%) in CPCO1, the richest source of peroxides (PV = 4.61 meq O_2/kg), indicated a lower magnitude of its hydrolytic deterioration. The reduction of FFA content in this oil can be attributed to lipase inactivation due to the thermal pretreatment of *Camelina sativa* seeds before the mechanical pressing. Nevertheless, insignificant differences in FFA amounts were observed between CPCO1 and CPCO6, as well as CPCO3 and CPCO4 also having similar levels of primary oxidation products (Duncan test, Table 4).

Table 4. Physicochemical properties of the cold-pressed camelina oils.

Parameter	Mean Value * ± SD							
	CPCO1	CPCO2	CPCO3	CPCO4	CPCO5	CPCO6	CPCO7	CPCO8
PV (meq O_2/kg)	4.61 ± 0.03 ^{f}	1.07 ± 0.03 ^{c}	1.12 ± 0.01 ^{c}	1.11 ± 0.04 ^{c}	3.37 ± 0.15 ^{e}	3.07 ± 0.03 ^{d}	0.58 ± 0.01 ^{a}	0.96 ± 0.02 ^{b}
AnV	0.25 ± 0.00 ^{b}	1.58 ± 0.08 ^{e}	0.29 ± 0.01 ^{b,c}	0.32 ± 0.01 ^{c}	0.15 ± 0.01 ^{a}	1.60 ± 0.05 ^{e}	0.79 ± 0.01 ^{d}	0.34 ± 0.02 ^{c}
FFA (%)	0.64 ± 0.02 ^{c}	0.88 ± 0.00 ^{e}	0.72 ± 0.02 ^{d}	0.68 ± 0.01 ^{d}	0.98 ± 0.02 ^{f}	0.63 ± 0.03 ^{c}	0.56 ± 0.03 ^{b}	0.42 ± 0.02 ^{a}
IP (h)	5.2 ± 0.1 ^{b}	4.8 ± 0.1 ^{a}	6.0 ± 0.2 ^{d}	6.6 ± 0.3 ^{e}	5.5 ± 0.2 ^{c}	5.0 ± 0.1 ^{a,b}	4.9 ± 0.1 ^{a,b}	6.8 ± 0.2 ^{e}
WVMC (%)	0.11 ± 0.00 ^{d}	0.16 ± 0.10 ^{f}	0.17 ± 0.00 ^{g}	0.05 ± 0.00 ^{a}	0.10 ± 0.01 ^{c}	0.07 ± 0.01 ^{b}	0.12 ± 0.02 ^{e}	0.11 ± 0.01 ^{d}
P (mg/kg)	11.55 ± 1.00 ^{f}	7.71 ± 0.20 ^{d}	10.03 ± 0.50 ^{e}	13.58 ± 0.41 ^{g}	4.77 ± 0.01 ^{c}	3.03 ± 0.23 ^{a}	4.17 ± 0.35 ^{b}	11.55 ± 0.95 ^{f}
B(a)P (µg/kg)	0.20 ± 0.01 ^{b}	0.13 ± 0.00 ^{a}	0.30 ± 0.00 ^{c}	0.30 ± 0.05 ^{c}	0.29 ± 0.01 ^{c}	1.90 ± 0.00 ^{d}	0.20 ± 0.01 ^{b}	0.20 ± 0.01 ^{b}
Chry (µg/kg)	0.21 ± 0.01 ^{b}	0.13 ± 0.01 ^{a}	0.69 ± 0.01 ^{d}	0.49 ± 0.02 ^{c}	0.91 ± 0.02 ^{e}	1.72 ± 0.08 ^{f}	0.20 ± 0.01 ^{b}	0.20 ± 0.01 ^{b}
B(a)A (µg/kg)	0.51 ± 0.01 ^{b}	0.27 ± 0.01 ^{a}	0.81 ± 0.01 ^{c}	0.50 ± 0.02 ^{b}	3.07 ± 0.15 ^{e}	1.91 ± 0.08 ^{d}	0.40 ± 0.02 ^{b}	0.50 ± 0.00 ^{b}
B(b)F (µg/kg)	0.19 ± 0.01 ^{a}	0.19 ± 0.01 ^{a}	0.41 ± 0.02 ^{c}	0.30 ± 0.02 ^{b}	0.40 ± 0.02 ^{c}	1.69 ± 0.04 ^{d}	0.21 ± 0.01 ^{a}	0.20 ± 0.01 ^{a}
∑4PAHs (µg/kg)	1.11	0.72	2.21	1.59	4.67	7.22	1.01	1.10

* n = 3; SD- standard deviation; different letters ($^{a–g}$) within the same row indicate significant differences between physicochemical parameters of cold-pressed camelina oils (one-way ANOVA and Duncan test $p < 0.05$). Abbreviations: PV—peroxide value; AnV—anisidine value; FFA—free fatty acids; IP—induction period; WVMC—moisture and volatile matter content; P—phosphorus content; B(a)P—benzo(a)pyrene; Chry—chrysene; B(a)A—benzo(a)anthracene; B(b)F—benzo(b)fluoranthene; ∑4PAHs—sum of four specific polycyclic aromatic hydrocarbons; CPCO—cold-pressed camelina oil.

As can be seen in Table 4, the results of PV, AnV, and FFA of all the studied CPCO samples were well within limits specified by Codex Alimentarius [43], up to 15 meq O_2/kg, 8, and 2%, respectively. In this way, amounts of oxidation products and the acidity of CPCO samples depend on several factors related to the freshness of *Camelina sativa* seeds, their varieties, technological processes, composition, storage, and marketing conditions of the final oils.

For comparison, cold-pressed camelina oils purchased from local grocery stores and small local manufacturers or directly pressed from *Camelina sativa* seeds had similar oxidative status monitored by PV (0.79–4.88 meq O_2/kg), AnV (0.22–1.60), and AV (0.25–1.90 mg KOH/g) or FFA (0.14–0.86%) [9,12,17,44,47]. Although the contents of secondary oxidation products in camelina oils cold-pressed at a temperature below 50 °C from one winter cultivar (Luna) and two spring varieties (Omega and Śmiłowska) were comparatively lower; thus, AnV varied from 0.20–0.28 [44]. Moreover, somewhat lower results of PV (0.80–1.15 meq O_2/kg), AnV (0.56–0.97), and acidity (0.123–0.433%) were reported for oils pressed from *Camelina sativa* seeds grown in different regions in Iran [10]. Deodorization of camelina oils also removed primary oxidation products, and fully refined oils contained a negligible amount of peroxides (PV = 0.18–0.40 meq O_2/kg) but a higher concentration of secondary oxidation products (AnV = 0.94–1.54) [18]. On the contrary, higher amounts of peroxides (PV = 2.5–10.0 meq O_2/kg) and secondary oxidation products (AnV = 1.0–1.8) were found in Norwegian crude cold-pressed camelina oil and centrifugated camelina oil stored during 12 months at 4 or 20 °C without air [1]. Additionally, the elongation of the storage time of camelina oils obtained from the seeds of plants grown in Slovenia to 11 months increased the formation of primary and secondary oxidation products (PV = 2.38, 10.6 and 50.6 meq O_2/kg and AnV = 6.2, 6.5, and 10.0 for fresh oil, and oils stored in darkness and exposed to light, respectively) [8].

On the other hand, oxidative stability is one of the most important parameters of oil quality for its potential commercial applications and utilizations in food and other commercial products. The oxidative stability of the investigated CPCO samples was determined using Rancimat analysis. The induction period (IP) for each of the eight commercial camelina oils was calculated, and the obtained IP results ranged between 4.8–6.8 h (Table 4). The Duncan test indicated that there were insignificant differences in IP results (4.8–5.0 h) for CPCO2, CPCO6, and CPCO7, with the highest content of PUFA (52.79–53.79%) (Tables 3 and 4). However, two samples, CPCO4 and CPCO8, revealed the highest oxidative stability (IP = 6.6 and 6.8 h, respectively). Overall, similarities and differences between the oxidative stability of the studied CPCO samples can be more dependent on the balance among its unsaturation level, antioxidants, and prooxidant components. Numerous factors, such as different origins and varieties of *Camelina sativa*

seeds, their maturity, mechanical damages, amounts of moisture and contaminations, conditions of cold-pressing, other technological processing, and storage, affect the oxidative stability of oils [17].

Similar resistance to accelerated oxidation (IP = 4.26–6.60 h) at 100 °C of cold-pressed camelina oils from retail outlets was estimated by Ratusz et al. [9], Szterk et al. [11], Raczyk et al. [12], and Symoniuk et al. [47]. Interestingly, IP values for oils pressed from *Camelina sativa* seeds cultivated in Poland, decanted, filtered, and then quantified using the Rancimat test at five different temperatures were between 0.45–0.70 h, 2.44–3.10 h, 4.58–5.63 h, 9.57–13.00 h, and 22.55–25.30 h at 120, 110, 100, 90, and 80 °C, respectively [17]. Generally, the breeding region had a significant effect on the oxidative stability (IP = 2.97–3.58 h at 110 °C) of oils cold-pressed from *Camelina sativa* seeds grown in four different temperate regions of Iran [10].

3.2.2. Water and Volatile Matter Contents

It is well known that water in oil can be dispersed as micro drops and stabilized by aggregation and dissolution of polar substances such as salts, free acids, diglycerides, phospholipids, alcohols, and phenols. For this reason, WVMC in oil should not be higher than 0.2%, which is the limit recommended by Codex Alimentarius [43]. On the other hand, WVMC in oils can also play a role in their stability and preservation of quality during storage and indirectly correlate with some sensory characteristics, such as pungency and bitterness [48].

The WVMC results for the investigated CPCO samples differed significantly and ranged between 0.05–0.17% (Duncan test, Table 4), corresponding to Codex Alimentarius [43]. It is noteworthy that the same WVMC of 0.11% characterized two samples, CPCO1 and CPCO8 (Table 4). These low WVMC levels could be related to the technological processes of CPCO samples and could influence their conservation by inhibiting the hydrolysis and oxidation processes.

To the best of our knowledge, WVMC data for camelina oils was not reported, whereas cold-pressed black cumin oils available for retail contained higher amounts of water and volatile matter (0.03–0.26%) [49,50].

3.2.3. Phosphorus Content

Measurement of P content in cold-pressed oil can be used to evaluate its quality and stability because phospholipids may act as antioxidants. The antioxidative activity of these components is attributed to their synergistic action, metal scavenging activity, and catalytic activity to decompose hydroperoxides. For this reason, the production of oil by using only cold-pressing without further refining allows preserving various valuable compounds, such as phospholipids with antioxidant properties, in the final product. Moreover, phospholipids have therapeutic properties. They could promote fat metabolism, decrease cholesterol levels, prevent cardiovascular diseases, and treat neurological disorders [51].

On the other hand, phospholipids can affect flavor generation due to the presence of unstable unsaturated fatty acids in phospholipid molecules. Additionally, vegetable oils with excessive phospholipids easily become flocculant during storage at room temperature, which affects consumers' acceptability, and intent to purchase is scarce.

The P content in commercial CPCO samples was determined using the official ICP-OES method [34], and the obtained results are listed in Table 4. As can be seen, the P amount in the studied CPCO samples ranged between 3.03–13.58 mg/kg, and insignificant differences in P concentration were observed between CPCO1 and CPCO8 (Duncan test, Table 4). Generally, the high P level in camelina oils significantly improved their oxidative stability. Thus, the analyzed CPCO samples with longer IP had higher P content (Table 4).

Fang et al. [52] explored the effect of different extraction methods on the amounts of phospholipids in camellia seed oils. They found that the phospholipid content (<3 μg/g) of the aqueous enzymatic-extracted oil and the supercritical CO_2-extracted oil was significantly lower than phospholipid concentrations in oils produced by expeller pressing

(about 6 μg/g) and hexane extraction (about 7 μg/g). However, camelina oils pressed from seeds cultivated in Iran contained significantly higher amounts of phospholipids (364.33–375.67 mg/kg) [10].

3.2.4. Polycyclic Aromatic Hydrocarbons Content

PAHs are hazardous, mutagenic, and carcinogenic chemical contaminants generated in vegetable oils during industrial production and from oil plants exposed to industrial and vehicular emissions. Technological processes at high temperatures, such as oilseed drying and roasting, solvent extraction, and long-duration frying, favor the formation of lipophilic PAHs in edible oils. Due to the lipophilic nature of PAHs, edible oils and fats can be the main source of these contaminants, and their analysis is necessary [53].

In this study, B(a)P, Chry, B(a)A, and B(b)F were determined and summed as ∑4PAHs to enable comparison with EU Regulation No 835/2011 [16] on contaminants limits in food, where B(a)P and ∑4PAHs are limited to 2.0 μg/kg and 10.0 μg/kg, respectively. The obtained results of each PAH content in the commercial CPCO samples are presented in Table 4. All analyzed oil samples had levels of B(a)P (0.13–1.90 μg/kg) and ∑4PAHs (0.72–7.22 μg/kg) below the maximum imposed by the EU Regulation No 835/2011 [16]. It is noteworthy that B(a)A was the analyte determined with the highest values in the interval 0.27–3.07 μg/kg. Interestingly, CPCO5 contained the highest B(a)A, whereas CPCO6 was the richest source of B(a)P, Chry, and B(b)F. Probably, the contact of *Camelina sativa* seeds with polluted surroundings and the drying process at high temperatures before CPCO6 pressing, by direct contact with combustion gases or migration of these contaminants to seeds from packaging bags, can cause PAH formation in the highest amounts [53,54]. Moreover, insignificant differences in concentrations of each measured PAH were observed between CPCO1, CPCO7, and CPCO8 (Duncan test, Table 4).

Regarding the results of B(a)P, Chry, B(a)A, B(b)F, and Σ4PAHs in eight commercial CPCO samples available on the Polish market, these were somewhat lower than values (B(a)P = 0.21–1.00 μg/kg, Chry = 0.21–4.40 μg/kg, B(a)A = 0.09–1.94 μg/kg, B(b)F = 0.05–1.89 μg/kg, and Σ4PAHs = 0.56–9.23 μg/kg) reported by Bartkiene et al. [15] in two camelina seeds oils prepared by artisans at small-scale agricultural companies in Lithuania. Furthermore, camellia oil pressed from untreated and treated camellia seeds powder with hot air and steamed with an electric steamer revealed a similar but higher amount of B(a)P (about 0.8 μg/kg) than investigated CPCO samples (except CPCO6). However, puffing pretreatment of camellia seeds powder significantly increased the B(a)P content to 1.3 μg/kg in oil [55]. Expectedly, much higher amounts of B(a)P (6.51 μg/kg) and ∑4PAHs (35.99 μg/kg) were determined in crude oil pressed from roasted camellia seeds at 100 °C for 30 min by using a low-temperature screw press [54]. Consequently, concentrations of B(a)P (0.86–7.44 μg/kg) and ∑4PAHs (5.21–41.32 μg/kg) changed in each stage of camellia oil refining, but decoloration caused the highest decrease in these contaminations. This suggests that high-temperature reactions during seed preparation (roasting, crushing), oil pressing, and refining processes (mainly deodorization), as well as absorbent used in filtration and decolorization, significantly affected the PAH levels in the obtained camellia oil [54].

The results of the oxidative stability, amounts of water, phospholipids, and contaminants in the studied camelina oils suggest that the utilized cold-pressing processes provided oils with a different ability to form oxidation products and degrade them as well as impacted various amounts of other undesirable components, which can be attributed to differences in the length of the pressing time and technological parameters such as seeds pretreatment, technical parameters of screw presses applied during pressing, operating temperature and further physical processes of oil purification.

3.3. Sensory Parameters as Discriminators of Cold-Pressed Camelina Oils

To the best of our knowledge, only a few studies in literature deal with the sensory analysis of camelina oils. For this reason, the QDA was applied to characterize and

discriminate between the CPCO samples available for retail, and obtained results are shown in Table 5.

Table 5. Score means of overall sensory quality, overall flavor intensity, and sensory attributes of cold-pressed camelina oils obtained by quantitative descriptive analysis.

Sensory Attribute	Mean Value * ± SD							
	CPCO1	CPCO2	CPCO3	CPCO4	CPCO5	CPCO6	CPCO7	CPCO8
OSQ	$4.5 \pm 0.1^{c,d}$	3.4 ± 0.2^{b}	4.3 ± 0.2^{c}	$4.5 \pm 0.2^{c,d}$	$4.5 \pm 0.2^{c,d}$	2.7 ± 0.0^{a}	4.6 ± 0.1^{d}	4.6 ± 0.1^{d}
OFI	$7.1 \pm 0.3^{b,c}$	4.5 ± 0.2^{a}	$7.0 \pm 0.2^{b,c}$	$7.3 \pm 0.2^{c,d}$	6.8 ± 0.3^{b}	4.5 ± 0.2^{a}	7.6 ± 0.1^{d}	8.0 ± 0.2^{e}
Taste and Flavor								
Bitter	0.0 ± 0.0^{a}	1.3 ± 0.1^{b}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	3.8 ± 0.1^{c}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}
Cabbage-like	4.3 ± 0.1^{d}	3.3 ± 0.1^{b}	4.8 ± 0.1^{e}	3.6 ± 0.1^{c}	3.1 ± 0.2^{b}	0.8 ± 0.0^{a}	5.1 ± 0.1^{f}	4.2 ± 0.2^{d}
Nutty-like	2.4 ± 0.1^{c}	0.8 ± 0.1^{a}	2.9 ± 0.1^{d}	3.4 ± 0.1^{e}	3.6 ± 0.1^{f}	1.2 ± 0.0^{b}	$3.5 \pm 0.1^{e,f}$	4.2 ± 0.2^{g}
Mustard-like	4.6 ± 0.1^{c}	3.1 ± 0.1^{b}	5.3 ± 0.2^{d}	5.3 ± 0.2^{d}	5.7 ± 0.1^{e}	1.2 ± 0.0^{a}	5.1 ± 0.1^{d}	5.8 ± 0.1^{e}
Fruity-like	3.7 ± 0.1^{d}	1.5 ± 0.1^{b}	3.7 ± 0.1^{d}	$3.8 \pm 0.2^{d,e}$	3.0 ± 0.1^{c}	0.5 ± 0.0^{a}	3.9 ± 0.1^{e}	4.3 ± 0.1^{f}
Woody-like	0.0 ± 0.0^{a}	1.9 ± 0.1^{d}	0.0 ± 0.0^{a}	0.5 ± 0.0^{b}	0.7 ± 0.0^{c}	4.9 ± 0.0^{e}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}
Mouth feeling								
Astringency	0.0 ± 0.0^{a}	2.1 ± 0.1^{b}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	5.2 ± 0.3^{c}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}
Persistence	0.0 ± 0.0^{a}	3.0 ± 0.1^{b}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	6.4 ± 0.2^{c}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}	0.0 ± 0.0^{a}

* n = 30 (10 assessors × 3 repetitions); SD—standard deviation; different letters ($^{a–g}$) within the same row indicate significant differences between attributes of the studied cold-pressed camelina oils (one-way ANOVA and Duncan test, $p < 0.05$). Abbreviations: OSQ—overall sensory quality; OFI—overall flavor intensity; CPCO—cold-pressed camelina oil.

The panel described the samples with ten sensory terms, and there were no detectable levels of negative taste and flavor attributes such as bitter, woody-like, astringency, and persistent mouth feeling in four samples: CPCO1, CPCO3, CPCO7, and CPCO8. These two negative mouth-feeling descriptions and bitter taste also were not noted in CPCO4. It is noteworthy that the scores of positive flavor descriptors such as cabbage-like (3.6–5.1), nutty-like (2.4–4.2), mustard-like (4.6–5.8), and fruity-like (3.7–4.3) for these five oil samples were significantly higher (Duncan test, Table 5). Moreover, the bitter taste was absent in CPCO5, while CPCO6 had the highest score for this attribute (Table 5). Interestingly, other negative flavor and mouth-feeling attributes, such as woody-like (4.9) and astringency (5.2), were judged to be of the highest intensity in this CPCO6 sample. Unexpectedly, persistence was not perceived for the CPCO6, whereas positive flavor attributes such as cabbage-like, nutty-like, mustard-like, and fruity-like had low scores ranging between 0.5–1.2. Generally, attributes that are considered negative (1.3–3.0) and positive (0.8–3.3) were detected at low and medium intensities in CPCO2.

PCA bi-pilot presented in Figure 1 was applied to the mean scores listed in Table 5 to interpret data from eight attributes, OFI, and OSQ measured on eight commercial CPCO samples.

The first two principal components accounted for 92.95% (PC1 = 81.33% and PC2 = 11.62%, respectively) of the total variation. The sensory results presented in Table 5 indicate a strong correlation in the sensory attributes assigned to the analyzed CPCO samples because the variability found in the samples is explained mainly by one component (PC1). PC1 negatively correlated with all positive attributes, such as OSQ (−0.9897), OFI (−0.9431), cabbage-like (−0.8776), nutty-like (−0.8561), mustard-like (−0.9727), fruity-like (−0.9820), while positively correlations were found between PC1 and negative descriptors: bitter taste (0.9694), woody-like flavor (0.9744), and astringency in mouth feeling (0.9794). However, PC2 was highly contributed only by one mouth-feeling attribute: persistence (−0.9966). It is noteworthy that OFI and positive flavor: cabbage-like and fruity-like were the variables with negative loadings on PC1 and positive loadings on PC2, whereas OSQ, nutty-like, and mustard-like were the features with negative loadings on PC1 and PC2 (Figure 1). As can be seen, PC1 clearly separates all CPCO samples with the acceptance sensory quality group (CPCO1, CPCO3, CPCO4, CPCO5, CPCO7, and CPCO8) from the unacceptance group (CPCO2 and CPCO6). Therefore, these six commercial oil samples characterized by good sensory quality scores (OSQ > 4.0) were located to the left in the score bi-plot. In

contrast, two oils with poor sensory quality scores (OSQ < 3.5) were situated at the right in the diagram and had positive values for PC1.

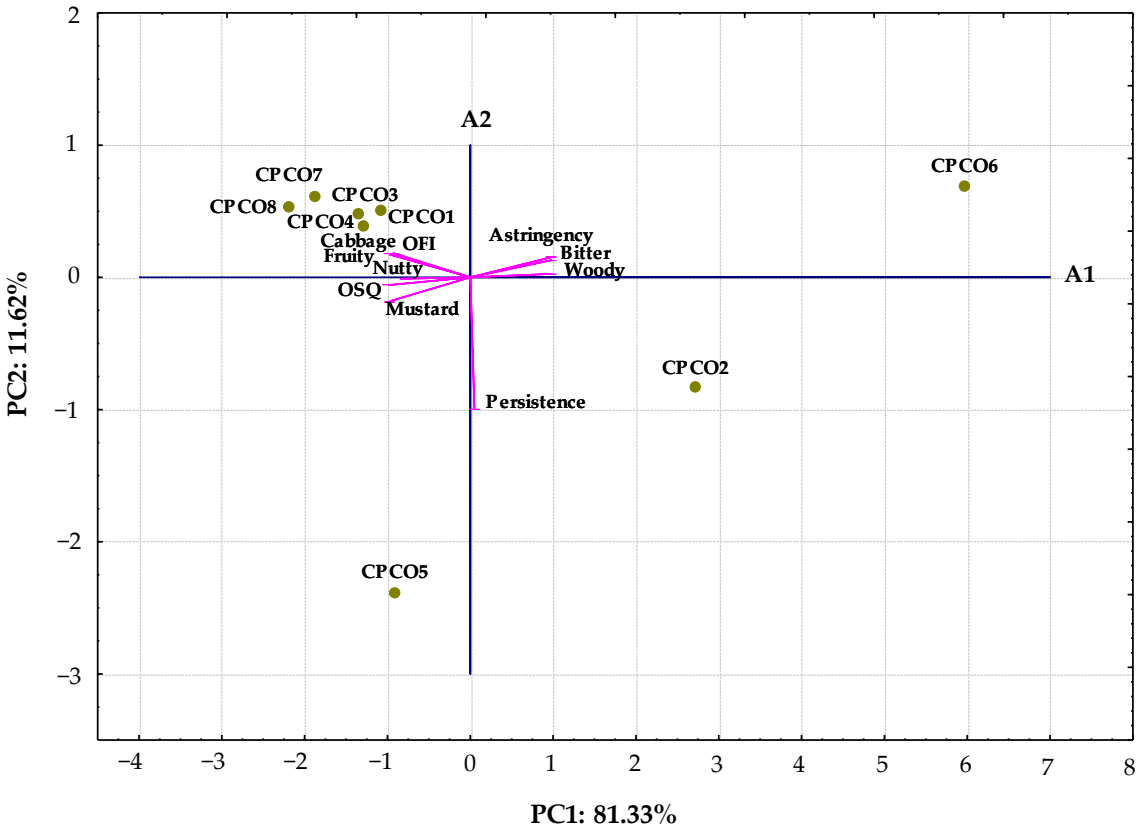

Figure 1. Principal component analysis of the sensory descriptors for the studied cold-pressed camelina oils.

Consequently, high positive correlations were found between the OSQ and OFI (r = 0.9423) and all positive sensory descriptors (r = 0.8276–0.9664), while negative correlations were calculated between the OSQ and negative attributes (r = −0.9545–−0.9745). Moreover, CPCO2 and CPCO5 with persistence in mouth feeling were located under the A1 axis. Interestingly, inappropriate storage conditions, the presence of impurities in raw material, or improper technology parameters can cause negative off-flavor attributes in cold-pressed oils [21].

However, two camelina oils available for retail in Slovenia had the most intense leafy and hay odor and aroma [22]. On the other hand, deodorization temperature affected the sensory properties of *Camelina sativa* oil. The oils deodorized at temperatures between 195–210 °C revealed satisfactory organoleptic results, while higher deodorization temperature caused the formation and appearance of off-flavor and odor [18].

It is well known that sensory quality plays a vital role in consumers' preferences, and it is beneficial for producers and traders to commercialize camelina oils. However, the sensory profiles of the investigated CPCO samples were probably influenced by various *Camelina sativa* seed cultivars used for cold-pressing oils, differences in technological processing, and the presence of the desirable and undesirable components in oils.

3.4. Relationships between Physicochemical Parameters and Sensory Quality of Cold-Pressed Camelina Oils Using Hierarchical Cluster Analysis

HCA was conducted to group the investigated CPCO samples available in the Polish market based on similarities in their fatty acid profiles, oxidative status and stability, contaminant contents, and sensory quality. Figure 2a depicts the dendrogram of the

commercial oils, while the dendrogram shown in Figure 2b proves the correlations between the analyzed variables.

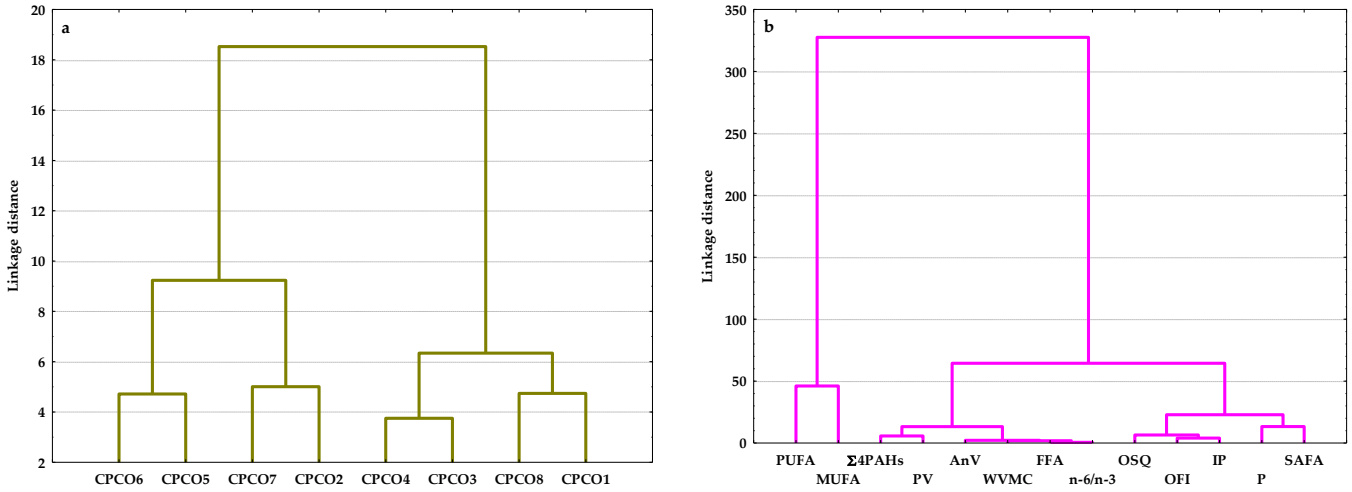

Figure 2. Dendograms of hierarchical cluster analysis for (**a**) the investigated cold-pressed camelina oil (CPCO) samples and (**b**) the studied variables.

In this analysis, two distinct clusters of CPCO samples formed, having different characteristics (Figure 2a). This dendrogram depicted a clear separation of CPCO2, CPCO5, CPCO6, and CPCO7 with the lowest ratio of n-6:n-3 and P content, the shortest IP, and a similar SAFA amount from the CPCO1, CPCO3, CPCO4, and CPCO8 with low concentrations of PUFA and secondary oxidation products (AnV), the longest IP, and the highest P content and OSQ scores (Tables 3–5). However, CPCO5 and CPCO6, with high content of primary oxidation products (PV) and ∑4PAHs, as well as CPCO2 and CPCO7 having the lowest MUFA amount, oxidative stability, and ∑4PAHs but the highest PUFA content, created two inter-clusters (Figure 2a). Moreover, the second cluster, including CPCO1 and CPCO8, was quite separated because these samples had the lowest levels of SAFA and PUFA, the highest MUFA content, as well as the same WVMC, P, and ∑4PAHs values. It can be noted that the physicochemical properties and sensory evaluation of the studied CPCO samples are different from one another.

In addition, similarities and discrepancies among physicochemical parameters, OSQ, and OFI of the commercial CPCO samples were determined using HCA and presented in Figure 2b. It is noteworthy that the concentration of unsaturated fatty acids in the studied oils (MUFA and PUFA) formed the first cluster. However, the second group was composed of two subgroups consisting of (I) parameters of oxidative status (PV, AnV, FFA), the ratio of n-6:n-3, undesired ingredients (∑4PAHs and WVMC), and (II) SAFA and P contents, oxidative stability analyzed by IP and sensory quality (OSQ and OFI). The obtained results confirm that SAFA and phospholipids as antioxidants can increase the oxidative stability of CPCO samples delaying the production of low-molecular-weight off-flavor compounds and oxidized components, improving their sensory quality. In contrast, unsaturated fatty acids susceptible to forming oxidation products (PV, AnV, FFA) and WVMC affected the oil quality by reducing its shelf-life and making it less acceptable to consumers or industrial use. Moreover, PAHs as organic hydrophobic contaminants are related to the safety of edible cold-pressed oils. The groups obtained by HCA demonstrated that a ratio of n-6:n-3 can contribute more to the hydrolytic status than the oxidative status of CPCO samples, whereas oxidative stability determined by IP impacted OFI more than OSQ (Figure 2b). Therefore, there were positive (p = 0.001752–0.2041) relationships between IP and OFI (r = 0.6195), OSQ (r = 0.5028), P content (r = 0.7149) and n-6:n-3 ratio (r = 0.9091) (Figure 3).

Figure 3. Correlation matrix between physicochemical parameters and sensory quality of cold-pressed camelina oils.

However, PV and ∑4PAHs variables created the inter-cluster because these results were positively correlated (r = 0.4471, p = 0.2667) (Figures 2b and 3). Interestingly, two sensory characteristics of CPCO samples had a positive (p = 0.08451–0.2255) association with P level (r = 0.4980 and r = 0.4829 for OSQ—P and OFI—P, respectively) and a ratio of n-6:n-3 (r = 0.5460 and r = 0.6445 for OSQ—n-6:n-3 and OFI—n-6:n-3, respectively). A significant positive correlation between OSQ and OFI also was found (r = 0.9423, p = 0.000460), whereas these two sensory parameters of investigated oils were negatively associated with the content of secondary oxidation products (r = −0.8906, p = 0.003009 and r = −0.8668, p = 0.005335 for OSQ—AnV and OFI—AnV, respectively). Additionally, correlation matrix results indicated significant negative correlations between MUFA and PUFA (r = −0.9485, p = 0.000329) and SAFA (r = −0.7742, p = 0.02413) determined in the studied oils (Figure 3). Furthermore, IP was negatively correlated to PUFA (r = −0.6883, p = 0.05911) and AnV (r = −0.6239, p = 0.09834). Meanwhile, P level and concentrations of ∑4PAHs (r = −0.6220), secondary oxidation products (r = −0.5429), and PUFA (r = −0.5277) also showed strong negative relationships (p = 0.09961–0.1789). In contrast, there was a significant positive correlation between the P amount and n-6 to n-3 ratio in oils (r = 0.7399, p = 0.03588).

The CPCO samples with high acceptance sensory quality regarding OSQ and OFI showed high values of n-6:n-3, IP, and P but low amounts of undesirable components such as secondary oxidation products and PAH contaminants.

4. Conclusions

This work evaluated, for the first time, the relationships between sensory descriptors, fatty acid profiles, and physicochemical parameters of commercial camelina oils produced by the cold pressing technique without applying heat, giving edible quality that did not require chemical refining. All CPCO samples available for retail are valuable in the human diet because ALA is the dominant essential fatty acid. Most importantly, none of the analyzed oil exceeded the upper limits for primary (PV < 15 meq O_2/kg) and secondary (AnV < 8) oxidation products, hydrolysis products of triglycerides (FFA < 2%), and toxic

contaminants such as B(a)P (<2 µg/kg) and ∑4PAHs (<10 µg/kg). Thus, low amounts of oxidative and hydrolysis products, moisture, volatile matter, P, and PAHs in CPCO samples available on the Polish market are not a public health concern.

In addition, the QDA method was done to gain a deeper insight into the sensory perception of eight commercial CPCO samples. Sensory attributes play a crucial role in appearance and flavor acceptability. Among the studied oils, two samples scored OSQ below 3.5 and OFI equal to 4.5 due to the presence of negative descriptors such as bitter taste, woody-like flavor, astringency, and persistence in mouth feeling.

The applied multivariate statistical analysis effectively assessed the quality of the CPCO samples and indicated the physicochemical and sensory parameters associated with the perception of product quality. The results obtained using these chemometric tools can be beneficial for the oil industries to monitor the quality of cold-pressed oils and develop new products to meet consumer needs.

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