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MACRONUTRIENT AND FATTY ACID CONTENT IN SELECTED SEEDS AND OILS AND THEIR USE IN DIETS FOR MONOGASTRIC ANIMALS*

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Abstract

Oilseeds play a key role in the nutrition of monogastric animals. The aim of the study was to analyze the basic chemical composition of various seeds: canola (*Brassica napus* L. var. *napus*), camelina (*Camelina sativa* (L.) Crantz), hemp (*Cannabis sativa* L.), soybean (*Glycine max* (L.) Merr.), nettle (*Urtica dioica* L.), grape (*Vitis vinifera* L.), sunflower (*Helianthus annuus* L.), and wheat germ (*Triticum aestivum* L.) and determine the fatty acid profile of oils extracted from these seeds. The nettle seeds had the highest crude ash content (12.96 g·100 g^{-1} dry matter, P=0.014). The soybean seeds were characterized by the highest crude protein content (38.02 g·100 g^{-1} dry matter, P=0.021). The sunflower seeds contained the highest ether extract content (53.1 g·100 g^{-1} dry matter, P=0.019) and the lowest crude fiber levels (2.23 g·100 g^{-1} dry matter, P=0.031). In terms of the fatty acid profile, the wheat germ oil had the highest level (P=0.023) of saturated fatty acids (SFAs). whereas the grape and hemp oils had the highest level (P=0.032) of polyunsaturated fatty acids (PUFAs), with predominance of linoleic acid, i.e. 71.3 and 64.2 g·100 g^{-1} ether extract, respectively (P=0.004). The camelina oil exhibited the highest amount of α-linolenic acid from the PUFA family (33.9 g·100 g^{-1} ether extract, P<0.001). The most favorable values of the atherogenic (P=0.009) and thrombogenic (P<0.001) indices were determined for the camelina, sunflower, and hemp oils. The analyzed seeds and oils used as feed material constitute an important source of linoleic and α-linolenic fatty acids, protein, and energy, partially or completely meeting the demand for these nutrients in the diets for monogastric animals. Continued research on the use of the analyzed seeds and oils in animal nutrition to increase production efficiency and support animal health may lead to their wider use in the husbandry sector.

Key words: plant materials, proximate chemical composition, essential fatty acids, pigs, broiler chicken, nutritional requirements

Oils and oil-bearing plant expellers play an important role in the global production of feed and food, as they account for approximately 79% of the total annual production (Fabjanowska et al., 2023). The current events (COVID-19 pandemic, war in Ukraine) clearly show the degree of interconnection and interdependence between the feed markets of individual countries. Therefore, it is essential not to rely only on only one feed market and source of raw materials but use local alternative feed sources. Currently, there is a noticeable increase in the interest in alternative sources of vegetable fat (Kowalska et al., 2017). The growing demand and consumer interest in these raw materials encourages the search for new sources of vegetable fat with a unique chemical and nutritional composition (Dorni et al., 2018). The circular economy represents a broad and comprehensive concept that promotes an innovative approach aimed at minimizing waste and using resources efficiently, e.g. in the agri-food sector (Pinotti et al., 2021; Govoni et al., 2023; Tretola et al., 2024). It supports the promising trend to use niche seed oils, such as grape seed and camelina oils (Costa et al., 2022; Juodka et al., 2022). The quality and quantity of fats in the diet exert a direct impact on the health of mammals (Aremu et al., 2015; Takumi et al., 2021). The fatty acid composition, characteristic of each plant, highlights the importance of incorporating fats from various sources into diets (Tancharoenrat et al., 2014; Baltić et al., 2017; Pi et al., 2019). Plant lipids containing saturated and unsaturated fatty acids as well as bioactive compounds, like α-tocopherol, are key elements in animal nutrition. They are a source of energy and bioactive substances in the organism (Ganesan et al., 2014; Kumar et al., 2020;

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Shadyro et al., 2020). Vegetable oils are a source of essential omega-6 fatty acids (linoleic acid (LA, C18:2)) and omega-3 fatty acid (α-linolenic acid (ALA, C18:3), which are not synthesized by animals and must be supplied in the diet for monogastric animals such as poultry and pigs. Their specific chemical composition supports the health status of the animals (Morya et al., 2022). The choice of an appropriate type of fat in animal nutrition is influenced by many factors, e.g. the species, age, sex, body weight, physiological condition, or type of animal production (Bayat et al., 2018; Avato and Tava, 2022).

Some literature reports indicate improved production of monogastric animals receiving niche seeds and oils in their diet. Such niche seeds as grape, hemp, camelina seeds, and their oils can be introduced into broiler or pig diets, as they exert a positive effect on the feed conversion rate and growth parameters in these animals (Abu Hafsa and Ibrahim, 2018; Hăbeanu et al., 2018; Zając et al., 2020; Mahmoudi et al., 2022). The presence of polyunsaturated fatty acids in the diet for young animals has an impact not only on improvement of production parameters but also on the immune response, intestinal health, and metabolism of the organism (Avato and Tava, 2022; Fabjanowska et al., 2023).

The addition of seeds and oils to animal nutrition schemes also has a beneficial effect on human health through improvement of the nutritional and dietary quality of animal products. The inclusion of PUFA-rich additives in the diet can increase the content of omega-3 and omega-6 fatty acids in animal meat and thus positively modify the dietary quality of fat, which also contributes to the improvement of human health by limiting e.g. the atherogenic effect of animal fat (Alagawany et al., 2019; Wang et al., 2021).

The aim of the study was to determine the basic chemical composition of seeds of canola (*Brassica napus* L. var. *napus*), camelina (*Camelina sativa* (L.) Crantz), hemp (*Cannabis sativa* L.), soybean (*Glycine max* (L.) Merr.), nettle (*Urtica dioica* L.), grape (*Vitis vinifera* L.), sunflower (*Helianthus annuus* L.), and wheat germ (*Triticum aestivum* L.), to analyze the fatty acid profile of oils extracted from the seeds, and to assess the possibility of introduction of these materials in the diet for monogastric animals in order to meet their nutritional demand for protein, energy, and both LA and ALA.

Material and methods

Plant materials

The investigations were conducted on 7 seed (canola, camelina, hemp, soybean, nettle, grape, and sunflower) and 1 germ (wheat) plant species used for large-scale and local or niche oil production. The characteristics of the analyzed seeds and the experimental design are shown in Table 1. Whole fresh plant materials (seeds and oils) were purchased in a specialist shop and the Seed Centre in 2022 (Lublin, Poland). As specified by the seller, the raw seeds originated from a farm localized in the south-east of Poland were the starting material for the production of cold-pressed oil produced on the farm.

Basic composition and fatty acids

The chemical analyses were performed in three replications of each combination of oilseeds and oils. The content of dry matter (d.m.) (Method 44-15A) and basic nutrients (crude ash – Method 08-01, crude protein – Method 46-06, ether extract (crude fat determined with the Soxhlet method) – Method 30-10) in the oilseed samples was determined according to standard AOAC (2019) procedures.

The nitrogen concentration was analyzed with Kjeldahl method, and crude protein was estimated as total N × 6.25. The content of nitrogen-free extracts (NFE) was calculated as the difference between the amount of dry matter and the total of the amounts of crude protein, crude fiber, crude fat, and crude ash. The energy value of the analyzed plant materials is based on the Atwater general factors for the energy density of fat, protein, and soluble carbohydrates (measured as nitrogen-free extracts (NFE) (9 and 4 $kcal \cdot g^{-1}$, respectively). Under the regulation of the European Parliament and the EU Council of 25 October 2011, the value of the coefficient was adjusted to the calorific value of fiber, i.e. 2 $kcal \cdot g^{-1}$ (Law Journal, 2011). The energy value of oilseeds expressed in kcal was converted to kJ (coefficient = 4.1868).

Table 1. Scientific and common names of experimental plants and abbreviations in the experimental scheme

Plant	Scientific name	Source[1]	Abbreviations in experimental scheme	
			raw seeds	oil
Canola	*Brassica napus* L. var. *napus*	Polish farm/factory oil press	BN.S	BN.O
Camelina	*Camelina sativa* (L.) Crantz	Polish farm/factory oil press	CmS.S	CmS.O
Hemp	*Cannabis sativa* L.	Polish farm/factory oil press	CnS.S	CnS.O
Soybean	*Glycine max* (L.) Merr.	Polish farm/factory oil press	GW.S	GW.O
Common sunflower	*Helianthus annuus* L.	Polish farm/factory oil press	HA.S	HA.O
Common wheat	*Triticum aestivum* L.	Polish farm/factory oil press	TA.G[2]	TA.O
Common nettle	*Urtica dioica* L.	Polish farm/factory oil press	UD.S	UD.O
Common grape	*Vitis vinifera* L.	Polish farm/factory oil press	VV.S	VV.O

[1]According to the information from the seller. [2]Wheat germ.

The fatty acid composition was determined with the gas chromatography method on a Varian CP-3800 chromatograph CP-3800 (Varian Inc., Palo Alto, USA) after conversion of the fats to fatty acid methyl esters (FAME) according to the AOAC method (1990) (Kiczorowska et al., 2019; Wu et al., 2007). Fatty acid methyl esters were identified via comparison against the retention times of 37 fatty acid methyl esters present in the standard mixture (Supelco 37 Component FAME Mix., No. CRM47885, Sigma-Aldrich Poznań, Poland). Fatty acids were grouped as saturated fatty acids (SFA) and unsaturated fatty acids (UFA): monounsaturated fatty acids (MUFA) and polyunsaturated fatty acids (PUFA). The atherogenic (AI) and thrombogenic (TI) indices and the ratio of hypo- and hypercholesterolemic fatty acids (HH) were calculated as follows:

$$AI = (4 \times C14{:}0 + C16{:}0) / (\sum MUFA + \sum(\omega\text{-}6) + \sum(\omega\text{-}3))$$

$$TI = (C14{:}0 + C16{:}0 + C18{:}0) / (0.5 \times \sum MUFA + 0.5 \times \sum(\omega\text{-}6) + 3\ x \sum(\omega\text{-}3)) + (\sum(\omega\text{-}3)/ \sum(\omega\text{-}6)$$

$$H/H = (C18{:}1\ \omega\text{-}9 + C18{:}2\ \omega\text{-}6 + C18{:}3\ \omega\text{-}3) / (C14{:}0 + C16{:}0)$$

The unsaturation index (UI) was calculated, with *trans* fatty acids considered as saturated, according to the following formula (Geiser et al., 1994):

$$UI = (1 \times (\%\ monoenes) + 2 \times (\%\ dienes) + 3 \times (\%\ trienes)) / 100.$$

Calculated dietary intake of nutrients in seeds and oil per portion for the daily demand coverage for animals

The daily intake of protein and energy by animals per one portion of the seeds and the intake of C18:2 and C18:3 fatty acids in oils by animals were calculated. Nutrients, i.e. energy and protein, important in the breeding/development cycle of monogastric animals (pigs and broiler chickens) were selected. The percentage coverage of the demand for energy and protein provided by a portion of seeds in adequate volumes was calculated for each animal species (broiler chickens – 10 g and pigs – 100 g), and 1% addition of oil to the complete mixture was taken into account for calculation of the degree of coverage of the demand for selected fatty acids. The calculations for the selected animal groups were carried out in accordance with the nutritional recommendations for poultry developed by the National Research Council (1994) and the Institute of Physiology and Animal Nutrition of the Polish Academy of Science (Grela and Skomiał, 2020) and by the National Research Council (2012) for pigs.

Statistical analysis

The data were analyzed with one-way analysis of variance ANOVA ($1 – \alpha = 95\%$; $P<0.05$), and the mean values for the treatments and the standard error of the mean were calculated using Statistica software (version 13.3; StatSoft, Tulsa, OK, USA). The Shapiro–Wilk and Brown–Forsythe tests were used for testing the normality of data and the homogeneity of variances, respectively. Significant differences between means were determined by Tukey's honestly significant difference (HSD) post hoc test.

Results

Basic nutrients in plant material

The analyzed plant material had similar dry matter content, with the exception of HA.S (sunflower seeds), which had 84.90 g·100 g^{-1} seeds of dry matter ($P<0.05$) (Table 2). The materials exhibited highly diverse levels of other nutrients. The UD.S (nettle seeds) material had the highest content of crude ash (12.96 g·100 g^{-1} dry matter) ($P<0.05$). The highest ($P=0.021$) total protein content was determined in GW.S (soybean seeds) and CnS.S (hemp seeds) (on average 37.52 g·100 g^{-1} dry matter), whereas the lowest amounts were found in VV.S (grape seeds) (12.51 g·100 g^{-1} dry matter). The HA.S and BN.S (canola seeds) samples contained on average 51.90 g· 100 g^{-1} dry matter of ether extract ($P=0.019$), while its lowest levels were determined in GW.S (17.62 g·100 g^{-1} dry matter). The level of fat in the analyzed components was also reflected in their calculated caloric value. The highest energy value ($P=0.027$) was calculated for BN.S. The analyzed components also differed in terms of their crude fiber content. The highest ($P=0.031$) level of crude fiber was determined in VV.S (44.38 g·100 g^{-1} dry matter), whereas HA.S contained only 2.23 g·100 g^{-1} dry matter of fiber. High variability was also found in the content of nitrogen-free extracts ($P=0.031$). The highest amounts were determined in TA.G (wheat germ) (24.06 g·100 g^{-1} dry matter). In turn, the CnS.S material was characterized by the lowest level of NFE (0.96 g·100 g^{-1} dry matter).

Fatty acids in plant material

The analyzed oils exhibited variable levels of saturated fatty acids ($P=0.023$) (Table 3). The highest content of SFAs was found in GW.O (soybean oil) (16.61 g·100 g^{-1} ether extract), and the lowest level was determined in HA.O (sunflower oil) and UD.O (nettle oil) (on average, 7.32 g·100 g^{-1} ether extract). The level of SFAs is largely determined by the content of palmitic acid (C16:0), and its highest ($P=0.027$) content was determined in TA.O (wheat germ oil) (17.1 g·100 g^{-1} ether extract). The average content of palmitic acid (C16:0) in the other analyzed oils was 6.03 g·100 g^{-1} ether extract (BN.O – canola oil, CmS.O – camelina oil, CnS.O – hemp oil, GW.O, HA.O, UD.O, VV.O – grape oil).

Table 2. Basic chemical composition (g·100 g⁻¹dry matter[1]) and energy value (ME, in 100 g dry matter) in the seeds of selected plants

Plants form	Dry matter g·100 g⁻¹ seeds	Crude ash	Crude protein	Ether extract	Crude fiber	Nitrogen-free extracts	Energy[2]	
							kcal	kJ
BN.S	94.00 a	4.23 a	31.17 ab	50.69 a	5.83 e	6.09 c	604 a	2529 a
CmS.S	93.98 a	3.87 c	25.62 b	36.79 b	28.51 b	5.21 c	548 ab	2294 ab
CnS.S	94.86 a	6.99 b	37.02 a	38.66 b	16.36 c	0.96 d	561 ab	2349 ab
GW.S	93.10 a	6.12 b	38.02 a	17.62 d	16.86 c	21.38 a	378 c	1583 c
HA.S	84.90 b	3.51 cd	24.10 b	53.10 a	2.23 f	1.96 d	583 ab	2441 ab
TA.G	93.97 a	6.30 b	30.62 ab	27.54 c	11.48 d	24.06 a	416 b	1742 b
UD.S	93.02 a	12.96 a	25.01 b	24.48 c	22.81 b	14.73 b	412 b	1725 b
VV.S	92.67 ab	3.12 a	12.51 c	21.09 cd	44.38 a	18.61 b	417 b	1746 b
Statistical parameters								
SEM[3]	0.315	0.021	0.278	0.183	0.175	0.478	7.150	12.07
P value[4]	0.032	0.014	0.021	0.019	0.031	0.031	0.027	0.019

BN.S – canola seeds; CmS.S – camelina seeds; CnS.S – hemp seeds; GW.S – soybean seeds; HA.S – sunflower seeds; TA.G – wheat germ; UD.S – nettle seeds; VV.S – grape seeds.

[1]Results are the average of three analyses; [2]Calculated as a simplified Atwater equivalent, in 100 g dry matter; [3]SEM – standard error of the mean; [4] P<0.05 – statistical differences; a, b, c, d – values in columns with different letters differ significantly (P<0.05).

Table 3. Chosen saturated fatty acids in seed oils (g·100 g⁻¹ ether extract[1]) from selected plants

FA	BN.O	CmS.O	CnS.O	GW.O	HA.O	TA.O	UD.O	VV.O	Statistical parameters	
									SEM[2]	P value[3]
C14:0	0.25 a	0.01 e	0.05 d	0.08 c	0.08 c	0.13 bc	0.04 d	0.07 cd	0.050	0.012
C16:0	5.95 c	5.81 c	5.75 cd	11.5 b	2.41 e	17.1 a	4.41 d	6.38 c	0.072	0.027
C17:0	0.11 ab	0.01 d	0.05 c	0.13 a	0.09 b	0.04 c	0.07 bc	0.14 a	0.015	<0.001
C18:0	2.08 bc	2.59 b	2.64 b	4.20 a	1.72 c	0.72 e	1.66 d	4.40 a	0.031	0.008
C20:0	0.27 e	3.24 a	0.90 c	0.36 de	2.57 b	0.19 a	0.60 d	0.20 e	0.016	<0.001
C22:0	0.23 c	0.41 c	0.37 bc	0.42 b	0.62 a	0.24 e	0.36 bc	0.11 d	0.007	<0.001
Σ SFA	8.89 de	12.1 c	9.76 d	16.61 b	7.49 e	18.4 a	7.14 e	11.3 c	0.203	0.023

BN.O – canola oil; CmS.O – camelina oil; CnS.O – hemp oil; GW.O – soybean oil; HA.O – sunflower oil; TA.O – wheat germ oil; UD.O – nettle oil; VV.O – grape oil.

C14:0 – myristic acid, C16:0 – palmitic acid, C17:0 – margaric acid, C18:0 – stearic acid, C20:0 – arachidic acid, C22:0 – behenic acid.

[1]Results are the average of three analyses; FA – fatty acids; SFA – saturated fatty acids; [2]SEM – standard error of the mean, [3]P<0.05 – statistical differences; a, b, c, d, e – values in rows with different letters differ significantly (P<0.05).

Table 4. Chosen unsaturated fatty acids in seed oils (g·100 g⁻¹ ether extract1) from selected plants

FA	BN.O	CmS.O	CnS.O	GW.O	HA.O	TA.O	UD.O	VV.O	Statistical parameters	
									SEM[2]	P value[3]
C16:1 ω-9	0.31 a	0.03 e	0.10 f	0.06 d	0.14 c	0.19 b	0.19 bc	0.15 c	0.009	0.025
C18:1 ω-9	55.2 a	14.7 d	14.8 d	18.3 c	27.3 b	17.8 c	57.0 a	14.0 d	0.138	<0.010
C20:1 ω-9	1.00 c	17.4 a	0.41 a	0.16 e	0.21 e	0.93 c	6.60 b	0.20 e	0.015	0.017
Σ MUFA	56.5 a	32.1 b	15.4 de	18.5 cd	27.6 bc	18.9 c	63.8 a	14.4 e	0.237	<0.010
C18:2 ω-6	24.1 d	19.9 d	54.4 c	55.6 c	64.2 b	56.1 c	21.1 d	71.3 a	0.215	0.004
C18:3 ω-3	10.3 c	33.9 a	20.4 b	9.22 c	0.73 f	6.46 d	7.85 d	3.00 e	0.189	<0.001
C20:2 ω-6	0.15 de	1.99 a	0.15 de	0.05 f	0.27 a	0.17 c	0.14 e	0.05 f	0.032	0.013
Σ PUFA	34.6 d	55.8 c	74.9 a	64.9 b	65.2 b	62.8 bc	29.1 e	74.4 a	5.270	0.032

BN.O – canola oil; CmS.O – camelina oil; CnS.O – hemp oil; GW.O – soybean oil; HA.O – sunflower oil; TA.O – wheat germ oil; UD.O – nettle oil; VV.O – grape oil.

C16:1 ω-9 – palmitoleic acid, C18:1 ω-9 – oleic acid, C20:1 ω-9 – gondoic acid, C18:2 ω-6 – linoleic acid, C18:3 ω-3 – linolenic acid, C20:2 ω-6 – eicosadienoic acid.

[1]Results are the average of three analyses; FA – fatty acids; MUFA – monounsaturated fatty acids; PUFA – polyunsaturated fatty acids; [2]SEM – standard error of the mean; [3]P<0.05 – statistical differences; a, b, c, d, e, f – values in rows with different letters differ significantly (P<0.05).

Table 5. Lipid parameters in selected plant oils, g·100 g^{-1} ether extract[1]

Lipid parameters	BN.O	CmS.O	CnS.O	GW.O	HA.O	TA.O	UD.O	VV.O	Statistical parameters	
									SEM[2]	P value[3]
UFA/SFA	10.25 b	7.290 c	9.250 bc	5.010 d	12.39 ab	4.440 d	13.01 a	7.850 c	0.111	0.022
MUFA/SFA	6.360 b	2.660 cd	1.570 d	1.110 e	3.680 c	1.030 3	8.940 a	1.270 de	0.093	<0.010
PUFA/SFA	3.890 e	4.630 de	7.670 ab	3.900 e	8.700 a	3.410 e	4.070 d	6.580 bc	0.015	0.018
AI	0.076 cd	0.067 d	0.066 d	0.141 c	0.029 f	0.215 a	0.049 e	0.075 c	0.027	0.009
TI	0.115 c	0.065 f	0.087 d	0.242 c	0.087 d	0.314 a	0.092 cd	0.209 b	0.072	<0.001
H/H	14.46 cd	11.77 e	15.44 c	7.210 f	37.01 a	4.670 g	19.31 b	13.69 d	0.098	<0.010
Total ω-3[4]	10.34 c	33.91 a	20.39 b	9.220 cd	0.730 f	6.460 d	7.850 d	3.000 e	0.136	0/029
Total ω-65	24.24 d	21.92 d	54.50 c	55.68 c	64.45 b	56.30 bc	21.21 d	71.35 a	2.030	0.015
ω-6/ω-3	2.34 d	0.65 e	2.67 d	6.04 c	88.29 a	8.71 c	2.70 d	23.78 b	7.430	<0.010
UI	105.3 c	76.96 d	125.0 b	130.1 b	156.5 a	131.7 b	106.5 c	157.1 a	4.980	0.018

BN.O – canola oil; CmS.O – camelina oil; CnS.O – hemp oil; GW.O – soybean oil; HA.O – sunflower oil; TA.O – wheat germ oil; UD.O – nettle oil; VV.O – grape oil; AI – atherogenic index; TI – thrombogenic index; H/H – ratio of hypo- and hypercholesterolemic fatty acids; UI – unsaturation index.

[1]Results are the average of three analyses; FA – fatty acids; MUFA – monounsaturated fatty acids; PUFA – polyunsaturated fatty acids; SFA – saturated fatty acids; [2]SEM – standard error of the mean, [3]$P<0.05$ – statistical differences; a, b, c, d, e, f, g – values in rows with different letters differ significantly ($P<0.05$); [4]Total ω-3 – C18:3 ω-3; 5Total ω-6 – C18:2 ω-6 + C20:2 ω-6.

Table 6. Percent coverage of daily supply of protein and energy in dry matter via consumption of one portion[1] of seeds by broiler chickens

Plants	Protein (g)	ME (MJ)	Protein (g)	ME (MJ)	Protein (g)	ME (MJ)
	Broiler chickens					
	starter		grower		finisher	
BN.S	31.51	4.45	11.72	1.43	8.49	0.93
CmS.S	25.90	4.04	9.63	1.29	6.98	0.84
CnS.S	37.43	4.14	13.92	1.32	10.08	0.86
GW.S	38.44	2.79	14.29	0.89	10.35	0.58
HA.S	24.37	4.30	9.06	1.38	6.56	0.90
TA.G	30.96	3.07	11.51	0.98	8.34	0.64
UD.S	25.29	3.03	9.40	0.97	6.81	0.63
VV.S	12.65	3.07	4.70	0.98	3.41	0.64
Mean	28.32	3.61	10.53	1.16	7.63	0.75
Daily recommendation[2]	9.89	0.57	26.6	1.78	36.72	2.73

BN.S – canola seeds; CmS.S – camelina seeds; CnS.S – hemp seeds; GW.S – soybean seeds; HA.S – sunflower seeds; TA.G – wheat germ; UD.S – nettle seeds; VV.S – grape seeds; ME – metabolic energy.

[1]One portion – 10 g; [2]Nutrient Requirements of Poultry (1994).

Table 7. Percent coverage of daily supply of protein and energy in dry matter via consumption of one portion[1] of seeds by swine

Plants	Protein (g)	ME (MJ)	Protein (g)	ME (MJ)	Protein (g)	ME (MJ)	Protein (g)	ME (MJ)	Protein (g)	ME (MJ)
	piglets		weaners		fatteners		pregnant sows		lactating sows	
BN.S	19.59	2.01	13.38	1.35	7.95	0.75	6.92	0.63	2.87	0.30
CmS.S	16.10	1.82	11.00	1.23	6.53	0.68	5.69	0.57	2.36	0.27
CnS.S	23.27	1.87	15.89	1.26	9.44	0.70	8.22	0.59	3.41	0.27
GW.S	23.90	1.26	16.32	0.85	9.70	0.47	8.44	0.40	3.50	0.18
HA.S	15.15	1.94	10.35	1.31	6.15	0.72	5.35	0.61	2.22	0.28
TA.G	19.25	1.39	13.14	0.93	7.81	0.52	6.80	0.44	2.82	0.20
UD.S	15.72	1.37	10.74	0.92	6.38	0.51	5.55	0.43	2.30	0.20
VV.S	7.86	1.39	5.37	0.93	3.19	0.52	2.78	0.44	1.15	0.20
Mean	17.61	1.63	12.02	1.10	7.14	0.61	6.22	0.51	2.58	0.24
Daily recommendation[2]	159.09	12.61	232.95	18.75	392.05	33.90	450.38	40.15	1085.51	85.94

BN.S – canola seeds; CmS.S – camelina seeds; CnS.S – hemp seeds; GW.S – soybean seeds; HA.S – sunflower seeds; TA.G – wheat germ; UD.S – nettle seeds; VV.S – grape seed; ME – metabolic energy.

[1]One portion – 100 g; [2]Grela and Skomiał (2020).

Table 8. Percent coverage of daily supply of fatty acids via consumption of one portion[1] of oils by broiler chickens

Plants	C18:2			C18:3		
	Broiler chickens					
	starter	grower	finisher	starter	grower	finisher
BN.O	24.09	15.82	24.09	227.48	197.94	210.94
CmS.O	19.93	13.09	19.93	746.02	649.13	691.76
CnS.O	54.35	35.70	54.35	448.58	390.32	415.96
GW.O	55.63	36.54	55.63	202.84	176.50	188.09
HA.O	64.18	42.16	64.18	16.06	13.97	14.89
TA.O	56.13	36.87	56.13	98.12	85.38	90.98
UD.O	21.07	13.84	21.07	172.70	150.27	160.14
VV.O	71.30	46.83	71.30	66.00	57.43	61.20
Mean	45.84	30.11	45.84	247.23	215.12	229.25
Daily recommendation	0.44[2]	1.34[2]	2.04[2]	0.02[3]	0.07[3]	0.10[3]

BN.O – canola oil; CmS.O – camelina oil; CnS.O – hemp oil; GW.O – soybean oil; HA.O – sunflower oil; TA.O – wheat germ oil; UD.O – nettle oil; VV.O – grape oil.
[1]One portion – 1%; [2]Nutrient Requirements of Poultry (1994); [3]Hovenier et al. (2006).

Table 9. Percent coverage of daily supply of fatty acids via consumption of one portion[1] of oils by swine

Plants	C18:2	C18:3	C18:2	C18:3	C18:2	C18:3	C18:2	C18:3	C18:2	C18:3
	Piglets		Weaners		Fatteners		Pregnant sows		Lactating sows	
BN.O	237.53	169.92	255.09	492.70	254.00	5451.25	241.83	8995.80	240.90	20507.67
CmS.O	196.51	557.25	211.04	1615.81	210.14	17877.35	200.07	29501.70	199.30	67254.83
CnS.O	535.89	335.08	575.51	971.58	573.07	10749.61	545.59	17739.30	543.50	40440.17
GW.O	548.51	151.52	589.06	439.33	586.56	4860.78	558.44	8021.40	556.30	18286.33
HA.O	632.81	12.00	679.59	34.78	676.71	384.86	644.27	635.10	641.80	1447.83
TA.O	553.44	73.29	594.35	212.52	591.83	2351.31	563.46	3880.20	561.30	8845.67
UD.O	207.75	129.00	223.11	374.05	222.16	4138.52	211.51	6829.50	210.70	15569.17
VV.O	703.02	49.30	754.99	142.95	751.79	1581.60	715.74	2610.00	713.00	5950.00
Mean	451.93	184.67	485.34	535.47	483.28	5 924.41	460.11	9 776.63	458.35	22 287.71
Daily recommendation	0.5[2]	0.3[3]	0.9[2]	0.2[3]	2.5[2]	0.05[3]	2.6[2]	0.03[3]	5.95[2]	0.03[3]

BN.O – canola oil; CmS.O – camelina oil; CnS.O – hemp oil; GW.O – soybean oil; HA.O – sunflower oil; TA.O – wheat germ oil; UD.O – nettle oil; VV.O – grape oil.
[1]One portion – 1%; [2]Nutrient Requirements of Swine (2012); [3]Smink et al. (2013).

The oils differed in the content of total monounsaturated fatty acids (MUFAs) ($P<0.01$) (Table 4). Their highest amounts were determined in the UD.O and BN.O samples (63.8 and 56.5 g·100 g^{-1} ether extract, respectively). CnS.O and VV.O were characterized by the lowest proportion of MUFAs, i.e. on average 14.9 g·100 g^{-1} ether extract. The amount of MUFAs is mainly determined by the content of oleic acid (C18:1 n-9); its highest level was found in UD.O (57.0 g·100 g^{-1} ether extract), while the lowest content was detected in VV.O (14.0 g·100 g^{-1} ether extract). The lowest proportion in the MUFA profile of the analyzed material was ascribed to palmitoleic acid (C16:1), with the highest ($P=0.025$) amount determined in BN.O (0.31 g·100 g^{-1} ether extract) and the lowest level found in the GW.O and CmS.O samples (on average 0.05 g·100 g^{-1} ether extract). The highest total PUFA content was determined in the CnS.O and VV.O samples (74.9 and 74.4 g·100 g^{-1} ether extract, respectively). This was associated with the high ($P=0.004$) level of LA (C18:2 n-6), which was the highest in VV.O (71.3 g·100 g^{-1} ether extract). Similarly, the content of ALA (C:18:3 n-3) in crude fat was high ($P<0.001$), with the highest level determined in CmS.O (33.9 g·100 g^{-1} ether extract).

Lipid parameters in raw and processed seeds

The analysis of the UFA/SFA ratio confirmed the differences between the oils ($P=0.022$) (Table 5). Its highest value was calculated for the UD.O sample (13.01), and the lowest ratio was found in the case of GW.O (5.01). The highest value of the MUFA/SFA ratio was calculated for UD.O (8.94). An eight-fold lower MUFA/SFA value was determined for the TA.O and GW.O samples (on average 1.07). The analyzed oils also differed in terms of the PUFA/SFA ratio ($P=0.018$). The highest PUFA/SFA value was determined for HA.O and CnS.O (8.70 and

7.67, respectively), whereas a two-fold lower value of the ratio was obtained in the GW.O and BN.O samples (on average 3.90). The value of the atherogenic index (AI) varied as well (P=0.009). The lowest and highest values were calculated for HA.O (0.029) and TA.O (0.215), respectively. The TA.O sample had the highest (P<0.001) value of the TI index, while the lowest value of this index was calculated for CmS.O (0.065). The average TI value for the other oil samples was 0.139. The material was also characterized by a varied level (P<0.001) of the hypocholesterolemic/hypercholesterolemic ratio (H/H). The highest H/H value was determined for HA.O (37.01), while an almost eight-fold lower value (4.67) was obtained for the TA.O sample.

There were differences in the amounts of fatty acids from the ω-3 (P=0.029) and ω-6 (P=0.015) families. Among the analyzed oils, CmS.O was characterized by a high sum of ω-3 fatty acids (33.91 g·100 g^{-1} ether extract) and a favorable ω-6/ω-3 ratio of 0.65. In turn, the VV.O sample was characterized by the highest content of ω-6 fatty acids (71.35 g·100 g^{-1} ether extract) with a high ω-6/ω-3 ratio of 23.78. The calculated unsaturation index (UI) had the highest values for VV.O and HA.O (157.1 and 156.5, respectively). The lowest UI value, i.e. 76.96, was determined for CmS.O.

Calculated dietary intake of nutrients and selected fatty acids in seeds and oil protein and energy

One portion of the analyzed components contained in the feed mixtures for broiler chickens was found to cover the daily protein requirement at an average level of 28.32% in the starter period, 10.53% in the grower period, and 7.63% in the finisher period (Table 6). In turn the values of metabolic energy (ME) were 3.61%, 1.16%, and 0.75%, respectively.

The analyzed plant raw materials used in the feed ration may only slightly meet the daily protein and fat requirements in the individual technological groups of pigs (Table 7). One portion of these raw materials was found to provide on average 17.61% of the daily protein requirement in the piglets, 12.02% in the weaners, 7.14% in the fatteners, 6.22% in the pregnant sows, and 2.58% in the lactating sows. In the case of ME, these values ranged from 0.24% to 1.63%.

Linoleic and α-linolenic acids

The inclusion of the optimal amount (1%) of oils from the seeds of the selected plants in the feed ration ensured a high supply of polyunsaturated fatty acids (PUFAs), especially LA and ALA (Table 8). In the case of broiler chickens, the addition of the oils covered on average 46% of the demand for LA in the starter and finisher period and 30% in the grower period. In turn, the addition of the analyzed oils resulted in two-fold higher levels of ALA than its daily recommended amount.

Given the low demand for LA and ALA fatty acids in pigs, the recommended levels of these components in the diet were significantly exceeded after the application of the oils (Table 9). The supply of LA in one dose was over four-fold higher than the daily recommended intake of this component. In turn, the supply of ALA with the oils from the seeds of the selected plants contributed to its variously elevated amounts, depending on the technological group: from almost two-fold in the piglets to over two hundred times in the lactating sows.

Discussion

Basic chemical composition

Seeds of oil-bearing plants are considered a valuable source of many nutrients (especially fat) in animal nutrition (Das et al., 2017; Plata-Pérez et al., 2022). The chemical composition of plants is influenced by many factors, i.e. it depends primarily on the species, variety, and environmental determinants (soil, weather conditions, agrotechnical treatments). Therefore, plants may exhibit a fairly variable chemical composition (Avato and Tava, 2022). As reported by Ítavo et al. (2015) and Lančaričová et al. (2021), alterations in the chemical composition within a plant species, as in the case of hemp seeds, may also result from changes in moisture absorption, topographic and climatic factors, and seed drying and storage methods. All the plant seeds tested in this study were characterized by a high concentration of nutrients (on average 92.5 g·100 g^{-1} seeds) (Table 2). Only the fat-rich sunflower seeds contained a lower amount of dry matter. Similar variability was also observed by Kiczorowska et al. (2019). The sunflower seeds exhibited the highest content of fat, and this finding is in agreement with the results reported by Zając et al. (2020), who established the level of this nutrient at 492 g·kg^{-1} dry matter. In turn, Alonso-Esteban et al. (2022) investigated hemp seeds and found that the fat content in this material was almost two-fold lower than that determined in the present study. The variability in the chemical composition of oilseeds was also highlighted by Delaev et al. (2019), who reported a range of 39.59– 42.19% of ether extract in soybean seeds. In addition to their high fat content, oil plant seeds provide significant amounts of protein (Kotecka-Majchrzak et al., 2020). As expected, the highest protein content (on average 37.5 g·100 g^{-1} dry matter) was determined in the seeds of high-protein plants, such as canola, hemp, and soybean, which was also confirmed by Sharma et al. (2014). Large differences in the protein content in hemp seeds were reported in the literature. The protein content determined by Mierlita (2016) and List (2016) was approximately 35% lower than that shown in the present study.

Seeds of plants used in other agricultural sectors, e.g. grape seeds, are interesting nutritional additives to be used in animal production. Large amounts of such seeds are residues of the processing of grapes. These seeds also exhibit a significant variability in their composition, which is highly influenced by the variety of grapes. As reported by Ovcharova et al. (2016), seeds of table and white grapes contained lower protein amounts, ranging from 60 to 90 $g \cdot kg^{-1}$ d.m., than seeds of red and wine grapes. The seeds of these grapes also had approximately 20% lower ether extract content than that established in the present study. The variability of the chemical composition of grape seeds and their seed oil yield was also reported by Elagamey et al. (2013). However, the amount of crude ash determined in their study was comparable to that shown in the present study. Grape seeds are considered valuable in animal nutrition not only due to their content of basic nutrients but mainly due to the presence of bioactive compounds contained therein, e.g. oligomeric proanthocyanidins with strong antioxidant activity or biologically active flavonoids (Hussein and Abdrabba, 2015). However, their application in the nutrition of monogastric animals, especially growing animals, may be limited by their relatively high content of crude fiber.

Equally interesting feed raw materials for use in animal production are nettle seeds, which are especially often used locally in extensive or organic production systems (Vaarst et al., 2006; Loetscher et al., 2013). Nettle seeds have exceptionally high content of crude ash, i.e. almost 13% in the present study. Their composition is dominated by P, Ca and Fe, and they also contain quite high concentrations of rare elements, e.g. titanium (Rutto et al., 2013). As shown by Adhikari et al. (2016), the content of raw ash in nettle powder can reach up to 16%, including up to 166 $mg \cdot 100\ g^{-1}$ d.m. of Ca and 228 $mg \cdot 100\ g^{-1}$ d.m. of Fe. The authors report that nettle powder is probably one of the richest sources of minerals among plant raw materials. The nettle seeds analyzed in the present study were found to have a relatively high level of total protein, i.e. 25.0 $g \cdot 100\ g^{-1}$ d.m. Such high protein content (almost three-fold higher than in cereal raw materials) was confirmed by Adhikari et al. (2016), who determined a level of 33.6% d.m. of protein in nettle powder. Nettle protein has a better amino acid profile than most other leafy vegetables and, with the exception of leucine and lysine, contains higher concentrations of other essential exogenous amino acids (Rutto et al., 2013). The nutritional interest in nettle and its seeds is mainly associated with its pro-health properties related to the presence of numerous bioactive substances. Medicinal herbs and dietary plants contain phenolic compounds: phenolic acids, flavonoids, tannins, stilbenes, curcuminoids, coumarins, lignans, and quinones. They exhibit strong chemopreventive properties, e.g. antioxidant, anticancer, antimutagenic, and anti-inflammatory activity (Rahmani et al., 2024).

In the nutrition of monogastric animals, especially poultry, wheat grain is the main component of complete feed mixtures. However, breeders in intensive animal production are increasingly willing to reach for unconventional feed raw materials that are available locally and very positively assessed by consumers of animal products, e.g. wheat germ. This feed raw material is relatively rich in crude protein and ether extract present in a range of 30.62 and 27.54 $g \cdot 100\ g^{-1}$ d.m., respectively. Mahmoud et al. (2015) reported similar contents of these nutrients in wheat germ. The authors emphasize its high biological value, which makes it an alternative source of protein to be used in other feeds. Wheat germ is a rich source of carbohydrates with their content of approximately 24 $g \cdot 100\ g^{-1}$ d.m. As confirmed by Mahmoud et al. (2015), the carbohydrate content in wheat germ can reach up to 46.07 $g \cdot 100\ g^{-1}$ d.m.; hence, it is an excellent source of energy (416 $kcal \cdot 100\ g^{-1}$ d.m.). Its suitability to be used as a feed component is supported by its low moisture content (approximately 6%), which is an indisputable advantage in terms of the storage and preservation of feed materials.

Fatty acid profile in vegetable oils and indices

As shown in Table 3, the fatty acid profile in the selected plant oils differed significantly between the analyzed plant species. The differences in the contents of the fatty acids and their groups can be associated with the differences in the plant varieties, geographical and climatic conditions of plant growth, the nutritional richness of the cultivation site, and the extraction methods used during oil production (Brandolini and Hidalgo, 2012; Schulte et al., 2013; Mitrović et al., 2023).

Among the oils tested in this study, the wheat germ and soybean oils had the highest levels of saturated fatty acids with the highest content of palmitic acid. The soybean oil comprised almost 17% of SFAs, with palmitic acid accounting for as much as 70% of the total SFA pool. The FoodData Central database of the US Department of Agriculture (2024) reported similar levels of saturated fatty acids in soybean oil, i.e. 14.9 g, and palmitic acid, i.e. 10.3 g in 100 g of oil. In turn, as specified by this database, the content of saturated fatty acids in oil extracted from wheat germ is 18.8 g, with the level of palmitic acid (the second most abundant fatty acid in this oil) of 16.6 g in 100 g of oil. These values are very similar to those obtained in the present study (18.4 g and 17.1 g, respectively). As demonstrated by other literature reports, the amount of palmitic acid in this oil may range from 13 to 20% (Barnes, 1983; Morrison, 1988; Eisenmenger and Dunford, 2008; Brandolini and Hidalgo, 2012). Among the oils assessed in the present study, the nettle oil had the lowest SFA content (7.14 g). The results of previous studies on the fatty acid composition in nettle seed oil indicate quite diverse SFA levels ranging from 2 to 13% (Uluata and Özdemir, 2012; Petkova et al., 2020; Mitrović et al., 2023).

In the present study, the analyzed vegetable oils exhibited different proportions of monounsaturated and polyunsaturated fatty acids (Table 4). The nettle and canola oils had the highest MUFA content (64% and 57%, respectively), with oleic acid as the most abundant MUFA representative (57 and 55 g, respectively). Therefore, these oils can be classified as oleic-type oils with three-fold higher oxidative stability than linoleic-type oils, i.e. almost all the other oils analyzed in this study. The fatty acid profile in oils has an impact on their oxidative stability. Oils with high contents of polyunsaturated fatty acids and lower levels of monounsaturated and saturated fatty acids undergo faster oxidation reactions. The fastest oxidation reaction takes place in linolenic acid, followed by linoleic and oleic acids (Liu and White, 1992; Mao et al., 2020). However, as reported by Petkova et al. (2020) and Mitrović et al. (2023), nettle seed oil has lower amounts of oleic acid (16.2 g and 12.03 g, respectively) and significantly higher amounts of LA (77.7 and 86.05 g, respectively). As proposed by the authors, it can be classified into the group of linoleic-type oils with pronounced oxidative stability.

The other analyzed oils contained mainly polyunsaturated fatty acids (56%–74%), including those exogenous to animal and human organisms (Bouchenak and Lamri-Senhadji, 2013; Wu, 2018), e.g. LA (20–71%) and ALA (0.7–34%). The oils extracted from camelina (CmS.O) and hemp (CnS.O) seeds were characterized by a particularly high level of ALA (33.9 g and 20.4 g, respectively). Other authors reported similar contents (from 27.1 g to 39.7 g) of this fatty acid in hemp oil (Budin et al., 1995; Zubr, 1997, 2003; Eidhin et al., 2003 b; Abramovic and Abram, 2005). The content of ALA in hemp oil shown by literature data is in the range of 15–25 g (Calloway and Laakkonen, 1996; Deferne and Pate, 1996; Matthäus et al., 2006), which is similar to that determined in this study. Nevertheless, it should be noted that the high content of ALA fatty acid is responsible for the susceptibility of the oil to oxidative rancidification (Ghafoor et al., 2017).

The pro-health quality of the tested oils was also assessed by determination of the sum of polyunsaturated fatty acids from the ω-3 and ω-6 families and calculation of their ratio (ω-6/ω-3), the ratio of polyunsaturated fatty acids to saturated fatty acids (PUFA/SFA), the ratio of hypocholesterolemic to hypercholesterolemic fatty acids (H/H), and the atherogenic (AI), thrombogenic (TI), and unsaturation (UI) indices (Table 5). The PUFA/SFA ratio plays an important role in various properties of cell membranes that help maintain proper metabolism in cells (Chang and Huang, 1998; Kang et al., 2005). Particularly high values of the PUFA/SFA ratio were obtained for the sunflower seed oil (HA.O), which also had substantial amounts of LA (64.2 g). This was also confirmed in studies conducted by other authors (Talebi et al., 2024). Similarly, the unsaturation index (UI) indicating the degree of unsaturation of fat had one of the highest values (156.5) in the case of the sunflower oil. This index determines the impact of highly unsaturated fatty acids but does not ignore the effect of fatty acids with a low unsaturation degree (Chen and Liu, 2020).

The nettle seed oil was also characterized by highly desirable health quality parameters related to its fatty acid profile. The UFA/SFA and MUFA/SFA ratios in this oil were significantly higher than in the other oils assessed in the study. The atherogenic (AI) and thrombogenic (TI) indices of the nettle seed oil were also low (0.049 and 0.092, respectively), which indicates its antiatherosclerotic and antithrombotic properties. This is also confirmed by the AI and TI values calculated for this oil (0.043 and 0.093, respectively) by Petkova et al. (2020). The atherogenic index AI indicates the relationship between the sum of saturated (proatherogenic) fatty acids and the sum of unsaturated (antiatherogenic) fatty acids (Ulbricht and Southgate, 1991). In turn, the thrombogenic index (TI) indicates the tendency to form clots in blood vessels and describes the relationship between saturated (prothrombogenic) fatty acids and unsaturated fatty acids with antithrombotic activity (MUFA, ω-6 PUFA, and ω-3 PUFA) (Ulbricht and Southgate, 1991). The very high hypocholesterolemic potential of the analyzed nettle seed oil is evidenced by the high value of the ratio of hypocholesterolemic fatty acids to hypercholesterolemic fatty acids (19.31). This indicator is used to assess the effect of the fatty acid profile on cholesterol levels and the risk of cardiovascular diseases (Chen and Liu, 2020). Its slightly higher value (24.993) calculated for nettle seed oil was reported by Petkova et al. (2020).

Potential use of the analyzed plants in the nutrition of monogastric animals nutrients

Animal nutrition is a key factor in the sustainable development of breeding, especially in the intensive production of monogastric animals (Barzegar et al., 2020; Ji et al., 2017). A challenge in one-sided feeding with plant feeds is to ensure the supply of protein with an appropriate amino acid composition (Beski et al., 2015). The most common source of protein in the diet of monogastric animals is soybean, which is characterized not only by high content of this nutrient but also by a favorable amino acid profile. The feed market is dominated by genetically modified soybean, and its use in animal production is increasingly arousing opposition from the consumers of animal products. Additionally, the carbon and nitrogen footprint associated with soybean production evokes consumer resistance and negation of its use (Eugenio et al., 2022). This prompts the need to seek and use alternative sources of protein in modern animal production (Florou-Paneri et al., 2014; Garcia-Launay et al., 2014).

In Poland, canola is considered one of the good and commonly used sources of protein with the greatest similarity of the amino acid profile to that of soybean, especially in terms of the presence of essential AAs necessary for monogastric animals (lysine, methionine, and threonine) (Chen et al., 2015; Alagawany et al., 2021; Zhang et al., 2021).

The present analysis of the potential of the nutritional use of the studied plants showed that hemp seeds can be a good source of protein and energy for poultry and pigs (Tables 6 and 7). One portion can cover up to 38% of the protein demand in a mixture for broiler chickens (starter) and up to approximately 23% of the demand for this nutrient for piglets (post-weaning mixture). These observations are confirmed by the findings reported by Mahmoudi et al. (2022), who used hemp seed supplementation of the diet for one-day-old Ross 308 broiler chicks at a dose of 2.5, 5, and 7.5% and described its beneficial effect on the growth parameters of the birds, i.e. the relative growth rate, body weight at maturity, improvement of the growth curve, and body weight at its turning point. In turn, studies on pigs conducted by Hăbeanu et al. (2018) showed that a 5% addition of hemp seeds to the diet of 10 Topigs hybrid sows for 21 days increased the milk yield and improved the daily weight gains of piglets in the first week of life.

Camelina seeds seem to be an equally good source of protein and fat nutrients. A study conducted by Zając et al. (2020) on 200 Ross 308 birds receiving a 15% camelina dose in the second and third rearing periods confirmed the beneficial effect of the supplementation on body weight gains of the birds in the last fattening phase, compared to the control group. The validity of introduction of camelina seeds in feed mixtures was also studied by Luise et al. (2024) in nutritional studies on piglets in the post-weaning period. Feed mixtures were supplemented with 4%, 8%, or 12% of camelina cake (CAM) for 28 days. The additive contributed to reduction in piglet growth performance and an increase in the mass of liver. As suggested by the authors of the study, in order to eliminate the presence of antinutritional factors in camelina seeds and promote their wider use in pig nutrition, they are recommended to be processed appropriately to improve their nutritional composition and digestibility.

The analysis of the potential use of wheat germ as a source of protein and energy in feed mixtures for poultry and pigs revealed promising results in terms of the nutrition for broiler chickens in each rearing period and pigs. This is confirmed by the results of studies conducted by other researchers in this field. A study was carried out by Gołuch et al. (2023) on the replacement of wheat meal with wheat germ cake at a concentration of 5, 10, and 15% as a feed additive to the diet for chickens. The research showed that the addition of a 5% wheat germ additive to the mixture was optimal because it did not deteriorate the basic chemical composition of the muscles and increased the content of P, Na, and Ca therein, although the recorded effective indicators of rearing chickens were slightly lower than in the control group. A study conducted by Brestenský et al. (2013) on cannulated growing pigs with an initial body weight of approximately 34.8 kg confirmed the beneficial effect of the wheat germ addition on the production performance of these animals. Sows were fed a mixture containing wheat germ, malt sprouts, and broken rice. The highest standardized ileal digestibility of amino acids was found in the group of animals fed with broken rice (0.96) and wheat germ (0.84), while the lowest value was obtained in the group receiving malt sprouts (0.61). In terms of the content of crude protein and digestible amino acids, the authors indicated soybean meal and wheat germ as the best sources of digestible protein for pigs (Brestenský et al., 2013).

There are literature reports indicating different production responses of monogastric animals receiving grape seeds in their diet. The grape seeds used in the present study did not seem to be a good source of protein or fat; they also contained crude fiber, which is a limitation for their use in poultry and pig rearing. In contrast, the results of a study on poultry reported by Abu Hafsa and Ibrahim (2018) are very promising. In a 42-day study on 300 one-day-old Cobb 500 chicks, the researchers found that the addition of grape seeds in a dose of 10, 20, and 40 $g\cdot kg^{-1}$ of feed improved feed efficiency and weight gain and had a positive effect on the feed conversion ratio (FCR) of the birds. Additionally, the experimental chickens were characterized by reduced populations of *Streptococcus* spp. and *Escherichia coli* and an increased count of *Lactobacillus* spp. in the ileum. Different results were obtained in experiments conducted on 22 TOPIGS-40 piglets (initial weight of 9 kg) receiving a feed mixture with an 8% addition of grape seeds for 30 days. The supplementation induced no significant changes in e.g. feed efficiency, body weight gain, or FCR (Grosu et al., 2020). Similar results were reported in Taranu et al. (2019, 2020), where the addition of grape seeds to feed mixtures for piglets had no effect on their production performance.

Linoleic and α-linolenic acid

Intensive production of monogastric animals forces breeders to use nutrition aimed at achievement of high production performance as well as ergonomic breeding and zootechnical work. This largely limits the natural mode of feeding birds and pigs by elimination of niche feed components with specific heath-supporting properties, which are otherwise instinctively consumed by livestock animals. Currently, feed mixtures for poultry and pigs are systemically enriched with bioactive compounds serving as a substitute for natural immunomodulators. These include e.g. PUFAs, especially LA and ALA. Numerous studies have confirmed their beneficial properties, e.g. improvement of health status by strengthening defense mechanisms, stabilization of intestinal microbiota, potential immunostimulatory effects leading to increased production performance, and even improvement of the quality of animal products, such as meat and eggs (Balenović et al., 2018; Alagawany et al., 2021; Makała, 2022; Swaggerty et al., 2022).

Linoleic acid is a nutrient that has to be supplied with the diet. In addition to its role as an energy source, it performs many functions in the animal organism. Linoleic acid is used in the organism to produce other omega-6 fatty acids, such as γ-linolenic acid (GLA), arachidonic acid (AA) from GLA, and tissue hormones from AA, which control the functions of organs locally and outside the nervous system. It is a building block for phospholipids (GLA), which are part of cell membranes. It is important for the structure of neuron cell membranes and retinal photoreceptors and determines the proper development of the nervous system and cognitive functions (AA) of animals (Lund and Rustan, 2024). It also regulates fat metabolism in the organism via reduction of the level of total cholesterol and LDL fractions, which is important in animal production targeted at meat characterized by high nutritional and dietary quality (Dinh et al., 2021).

The present analysis of the potential use of the tested plant materials to meet the demand for LA in broiler chickens and pigs showed that the best source in all rearing periods may be grape seed oil and sunflower seed oil, as one portion of these oils (1% of the mixture) covered approximately 71 and 64% of the demand for this FA in the first and second period of broiler chicken rearing, respectively. In all the technological groups of pigs: piglets, weaners, fatteners, and lactating sows, both oils covered approximately 703 and 633, 755 and 680, 752 and 677, 716 and 644, and 713 and 642% of the demand for this fatty acid, respectively (Tables 8 and 9).

There are many reports in the literature confirming the beneficial effect of dietary PUFAs on rearing performance. For example, in studies conducted on 120 Cobb 500 broilers, the addition of 1.5 and 3% of grape seed oil was tested as a source of natural antioxidants in the feed mixture. The birds achieved a higher body weight in the last phase of fattening. Their thigh muscles were characterized by a significantly higher degree of brightness and significantly improved oxidative stability (Turcu et al., 2021). In turn, in a study on broiler chickens, Panaite et al. (2020) found that the addition of grape seed oil (1.5 and 3%) to a PUFA-enriched broiler diet positively limited the growth of pathogenic bacteria in the small intestine, thereby improving the microbiological balance in intestinal digesta. The number of Enterobacteriaceae and staphylococci decreased in direct proportion to the increase in the dose of grape seed oil administered to the experimental birds. As suggested by Costa et al. (2022), higher levels of grape seed oil, even 2- to 3-fold higher than those applied in poultry production, should be used in pig production. The authors report that the beneficial effect of grape products on animal performance is mainly associated with their antioxidant, antimicrobial, and intestinal morphology-modulating properties.

The positive effect of sunflower oil on animal organisms was confirmed by Khatun et al. (2017). In experimental broilers (Cobb 500), they observed a higher body weight and better feed efficiency. Similarly, Liu et al. (2017) analyzed the effect of addition of 1 and 2% of soybean and sunflower oils to the feed ration for Ross 308 broiler chickens (from 1 to 42 days of age) and noted better feed efficiency. The soybean oil and sunflower oil included in the diets had positive effects on the health status of the birds, as they contributed to e.g. a significant increase in the levels of total protein, albumins, α-globulins, and β-globulins in the serum of the birds.

The beneficial effect of sunflower oil on animal health was also observed by Bezerra et al. (2020) in their study conducted on 180 piglets. The dietary supplementation with sunflower oil positively interfered in the systemic inflammatory response through the total leukocyte count and neutrophil/lymphocyte ratio, in the oxidant-antioxidant balance assessed by measuring nitric oxide and malondialdehyde, and in lipid metabolism determined by measurement of the level of total cholesterol and triglycerides.

In the case of ALA, the analysis of the potential of the tested oils to be used to cover the demand for this component in broiler chickens and pigs confirmed that camelina, hemp, and soybean oils can be a very good source of this FA in all rearing periods. One portion of these oils (1% of the complete mixture) can cover the demand for this fatty acid on average 6 times, 4 times, and almost 2 times, respectively, in the entire broiler chicken rearing period. The demand for ALA in pigs is lower; therefore, the oils exceeded the demand on average from several to over a dozen times in each technological group: piglets, weaners, fatteners, and lactating sows.

High nutritional suitability of camelina seed oil for achievement of high production performance was reported by Pietras and Orczewska-Dudek (2013), who introduced this oil in broiler chicken diets in doses of 3 and 6% of the feed mixture. The addition of 6% of the *Camelina sativa* oil significantly reduced the content of total cholesterol and its fractions in the blood plasma of chickens, compared to the other groups. The addition of 3% and 6% of this oil to the chicken diet enriched their breast muscles with ω-3 PUFAs, mainly ALA, and did not worsen the taste of cooked meat. A greater increase in ALA was found in the meat of chickens receiving 6% of the camelina seed oil. In another study, the doses of 40 and 100 $g \cdot kg^{-1}$ of camelina oil in feed mixtures for 456 Ross 308 broiler chickens aged 21–42 days modified the juiciness of breast muscles in addition to the dietary improvement of their FA profile (Orczewska-Dudek and Pietras, 2019).

Similar results of the use of camelina seed oil were also noted in pig production. A study was conducted on Large White pigs with an average weight of 67 kg, which were fed a mixture with camelina oil for 42 days. The supplementation resulted in a significant increase in the ALA level, a decrease in the level of triglycerides and cholesterol in the meat, and a decrease in the extracellular synthesis of superoxide anion (Hăbeanu et al., 2009). As reported by Eidhin et al. (2003 a), camelina seed oil can be a real alternative to traditional fat sources in pig diets without a negative effect on the feed intake. It was shown that commercial crossbred pigs fed diets containing 5% or 10% of camelina seed oil did not show any signs of reluctance towards consumption of mixtures containing this oil. Additionally, camelina seed oil exerted additional beneficial effects related to the modification of the lipid profile in pig blood plasma, i.e. reduction of the level of triacylglycerols, increased levels of ω-3 fatty acids, and reduced content of ω-6 fatty acids.

The relationship between the intestinal microbiota and the immune system of birds is still poorly elucidated. Although the link between ω-3 fatty acids (FAs) and immunity is well-established, the latest research indicates that ω-3 FAs and the gut microbiota share critical pathways of activation and inhibition of the immune system

(Thanabalan and Kiarie, 2021). Increased ω-3 FA intake has been reported to increase *Lactobacillus* bacterial counts. Lymphocytes B develop until sexual maturity in the bursa of Fabricius, a branching of the intestine near the cloaca. Bacteria residing in the bursa contribute to the development of the adaptive immune response in birds (Madej et al., 2013). The link between the ω-3 FA supply and the stability of the intestinal microbiota in pigs has been investigated as well. Zhang et al. (2020) confirmed that the use of ω-3 PUFAs not only improved dry matter and nitrogen digestibility in weaned piglets but also had a beneficial effect on the *Lactobacilli* count in feces.

Although the present analysis showed that hemp seed oil can be a good source of ALA in the production of monogastric animals, there are discrepant literature data on its production effects. As demonstrated by Stastnik et al. (2016), the use of hemp seed bioproducts (2.5% of hempseed expellers and 1% of pellets from technical hemp plant tops) in chicken nutrition did not exert a significant effect on the monitored microbiological parameters of intestinal digesta. Similarly, there were no differences in the average body weight of birds and carcass yield. The authors suggested that the 0.03% and 0.15% content of cannabidiol may have contributed to the absence of significant differences. The absence of significant improvement of production parameters in poultry was also confirmed by Vispute et al. (2019). Nevertheless, the authors emphasized that, despite the lack of significant improvement in bird rearing performance, the health status of the birds improved significantly, as reduced serum lipid concentrations (triglycerides, LDL, and total cholesterol) and lower aspartate aminotransferase (AST) and alanine aminotransferase (ALT) activity were observed. A linear reduction in the coliform bacterial count in the cecum and the jejunum was recorded, but no effect on the villus height and the depth of jejunal mucosa crypts was found.

On the other hand, literature data from research on pigs reported the immune response of these animals to ω-3 FA-rich nutritional factors. In a study conducted by Vodolazska and Lauridsen (2020), 24 Landrace×Yorkshire crossbred sows received experimental diets with 5% of hemp seed oil, 5% of soybean oil, or a 5% mixture (50:50) of hemp and soybean oils from day 108 of pregnancy until weaning (4 weeks after farrowing). The experiment showed that the inclusion of 5% of hemp seed oil or a 5% mixture of hemp and soybean oils in the sows' diet increased the level of IgA in piglet plasma at day 4 of life. At day 16 and 28 of life, the plasma IgM and IgG concentrations depended on the source of oil in the diet for the sows and had the highest values in piglets from sows fed the mixture of hemp and soybean oils.

Soybean products, both meal and oil, have a well-established position in the feed market and are widely used in animal production, especially in diets for monogastric animals. Both scientists and the production sector appreciate the nutritional and pro-health values of these feed materials. Recently, the interest in soybean oil has been increasing, and its health-enhancing and production effects have been confirmed by scientific research.

In an 8-week study conducted by Sanwo (2019) on 225 chicks, 100, 200, 300, and 400 $mg \cdot kg^{-1}$ doses of soybean oil were used with the addition of vitamin E. A significantly improved lipoprotein profile (triglycerides and cholesterol) was observed in the meat of the experimental groups. The diet also had a significant effect on meat taste, tenderness, overall acceptability, and meatiness, whereas no significant effect on meat color was observed. The microbiological analysis did not detect *Escherichia coli* or *Salmonella* spp. in stored samples.

Studies indicate that it is advisable to include vitamin E supplementation in diets rich in soybean oil, because this vitamin increases their oxidative stability. It should also be noted that dietary modifications that increase the PUFA content in animal tissues also result in greater susceptibility to oxidation and generation of free radicals. This has a negative effect on animal health and reduces the dietary value of animal products. Vitamin E is a natural inhibitor of oxidation processes in the organisms. The demand for this vitamin increases with the increase in the amount of polyunsaturated fatty acids in animal diets (Vieira et al., 2021).

Similar investigations were carried out by Alencar et al. (2021), where the effect of the level of soybean oil addition on the performance and fatty acid profile in the backfat and *longissimus lumborum* muscle of gilts was assessed. Forty-eight gilts with an initial weight of 21.75 kg and a final weight of 98.65 kg were exposed to one of six dietary soybean oil levels (0.00, 1.086, 2.173, 3.259, 4.345, and 5.432%). The inclusion of the soybean oil resulted in beneficial modifications of the lipid profile in the backfat and muscles, reduced the content of SFAs and MUFAs, and increased the content of PUFAs, mainly LA and ALA. The increased soybean oil content in the diet resulted in reduction of the atherogenic and thrombogenic indices and the omega-6:omega-3 ratio in the backfat and *longissimus lumborum* muscle. However, the doses of oils in feed mixtures for fattened animals should be selected with caution, as an excessive amount of PUFAs in meat may result in deterioration of its quality due to the high susceptibility of the fatty acids to oxidation (Wood and Enser, 2017).

Conclusion

The analysis of the nutritional value of the tested feed raw materials (seeds/germ) has shown that they can be a good source of basic nutrients, and the oils extracted from these materials provide linoleic and α-linolenic acids in the diet for monogastric animals. The nettle seeds proved to be the richest source of crude ash, the soybean seeds provided the greatest amounts of crude protein, and the sunflower seeds, which concurrently had the lowest amounts of crude fiber, were the best source of ether extract. In terms of the fatty acid profile, the highest SFA content was determined in the wheat oil, and the highest level of PUFAs, dominated by linoleic acid, was detected in the grape seed and hemp oils. The camelina oil exhibited the highest content of α-linolenic acid in the PUFA pool, and the most favorable AI and TI values were determined for the camelina, sunflower, and hemp oils. As shown by the analysis of the potential nutritional use of the tested plant materials, the canola, hemp, camelina, grape, and wheat germ oils can be a good source of protein and energy to be used in poultry and pig nutrition. The grape seed and sunflower seed oils turned out to have exceptionally high levels of linoleic acid. One portion of these oils (1% of the complete feed mixture) covered on average 70% of the demand for LA in the first and second periods of broiler chicken rearing and exceeded the demand (5–6 times) in all the technological groups of pigs analyzed in this study: piglets, weaners, fatteners, and lactating sows. Supplementation of the feed mixture with 1% of these oils can cover many times the demand for this fatty acid throughout the broiler chicken rearing period and from several to over a dozen times in pig production. All the analyzed plant feed components can be used in the production of monogastric animals; especially promising are the grape seed and wheat germ oils, which are currently used in niche applications. A continuation of animal research on their nutritional use in terms of production performance and health effects may lead to a wider use of these materials in the animal sector.

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