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Camelina sativa as a sustainable and feasible feedstuff for broiler poultry species: A review

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Abstract: *Camelina sativa* can be identified as a promising oilseed crop due to its short growth cycle, tolerance to drought and frost, low-input requirements, resistance to pests and diseases, feed, and non-feed applications. Compared to other Brassicaceae family plants, camelina is mainly distinguished by high levels of *n*-3 polyunsaturated fatty acids and antioxidant content. However, camelina contains secondary plant metabolites, such as glucosinolates, phytic acid, sinapine, etc., and their presence limits the use of camelina by-products (oil, seed or cake) in poultry feeding. The breakdown of these compounds forms complexes that can inhibit digestive enzymes, reduce the absorption of nutrients, and ultimately modify product quality. The content of these anti-nutritional compounds and plant seed quality can be modified by various techniques: hybridisation, mutation induction, gene engineering, etc. Moreover, methods such as infrared irradiation, multi-enzyme and copper supplementation, etc., can counter or mitigate the effect of plant secondary metabolites present in camelina seed or cake. In general, dietary inclusion of camelina seed or cake at high inclusion levels (> 10%) worsened the nutrient digestibility and thus reduced growth performances. However, carcass traits and meat proximate composition were comparable in birds-fed diets containing camelina by-products. The fatty acid profile of meat cuts and abdominal fat was significantly higher in alpha-linolenic acid and lower *n*-6/*n*-3 ratio, thus promoting the healthiness of products for human consumption. Also, the dietary inclusion of camelina did not modify the sensory profile of the products. The present article is a comprehensive and critical review of research carried out to improve the quality of camelina and its by-products to be used in broiler poultry feeding. This review gives information on the feeding value of camelina by-products, as well as a survey of the literature on their use in poultry diets to evaluate digestibility, performance, carcass traits, and meat quality.

Keywords: false flax; broiler; digestibility; performance; meat quality; fatty acid

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CAMELINA (*CAMELINA SATIVA* L. CRANTZ)

Camelina sativa is an oilseed plant that belongs to the Brassicaceae family. It is an annual dicotyledonous plant species with a short life cycle of 85–250 days. Camelina plant produces small self-pollinating yellow flowers with four petals organised as a raceme, stems are either smooth or hairy, branched, and become woody when it attains maturity. Flowers developed into pear-shaped silicles (16 to 115 silicles per plant) are around 4 to 5 mm in diameter and contain 10 to 20 seeds, depending on the genetics and growth conditions during seed development (Mondor and Hernandez-Alvarez 2021; Zanetti et al. 2021). During ripening, silicles change their colour from green to yellow-reddish and then completely dry at maturity. Camelina plants can reach final heights ranging from 0.65 to 1 m and can form up to 30 lateral branches. There are two camelina cultivars, i.e., spring and autumn; the spring cultivar is the most widespread worldwide (Zanetti et al. 2017, 2021).

Camelina is native to Europe and Southwest Asia, and it has an ancient history dating back to 4000 before the common era (BCE) while the first findings of camelina in Scandinavia are from 1800 BCE (early Bronze Age) (Zanetti et al. 2017; Mondor and Hernandez-Alvarez 2021). Some evidence demonstrates that camelina was present in Eastern Turkey between 700 and 900 BCE and in Romania in the transition from Eneolithic to Bronze Age, indicating that camelina was likely cultivated for its oil (Mondor and Hernandez-Alvarez 2021; Zanetti et al. 2021). Camelina has been occasionally cultivated, especially around its centre of origin, until the middle of the 20th century. Thereafter, more productive oilseed plants became the primary source of vegetable oil in Europe (Mondor and Hernandez-Alvarez 2021). Interestingly, in the last decade, camelina has been rediscovered and gained considerable attention, mainly in the case of scientific studies to improve the camelina lines, characterised by increased seed weight, seed yield, lower anti-nutritional factors, and improved lipids quality compared to the old camelina lines (Vollmann and Eynck 2015; Zanetti et al. 2021).

SUSTAINABILITY POTENTIAL AND CULTIVATION

Camelina sativa can be classified as a promising oilseed crop in terms of sustainability, as it requires relatively low agriculture inputs. This is because camelina plants are tolerant to drought, having the ability to extract water from much deeper compared to the other species. Camelina plants require just over half of the water in total compared to other oilseed crops grown in the same area and in a similar time frame (Zanetti et al. 2021). Furthermore, camelina plants tolerate low temperatures, and they are resistant to the common *Brassica* pests and diseases because they produce antimicrobial phytoalexins as a response to biotic and abiotic stresses (Mondor and Hernandez-Alvarez 2021; Zanetti et al. 2021).

Camelina can be cultivated as the main crop in marginal soils with both spring and autumn cultivars. However, camelina can also be utilised as a summer and winter cover crop in double cropping systems (Leclere et al. 2019; Zanetti et al. 2019). This approach widens the opportunities for camelina to pass from niche crop to cash crop. Cover crops are able to reach maturity before the establishment of the main crop, thus providing additional income to farmers (Gesch et al. 2014). Groeneveld and Klein (2014) demonstrated that growing camelina as a summer cover crop after strawberry, enhanced insect biodiversity, providing foraging resources at times when very few other plants are usually flowering. Similarly, Zanetti et al. (2019) demonstrated the feasibility of growing camelina as a winter cover crop before maise and other typical summer crops, including sunflower and soybean. Though, the choice of crop to match camelina should be carried out locally to fulfil farmers' expectations and needs.

One of the main advantages of camelina compared to the other competing crops, including other members of the Brassicaceae family, is the shorter life cycle, thus allowing the sowing of a second crop and likely aiding in reducing nematodes e.g., camelina has been reported to reduce nematodes cysts in soybean as it contains high level of glucosinolates. This chemical acts as a bio-fumigant agent. Also, the use of camelina in maise and soybean crop fields has been demonstrated to increase not only the biodiversity of crops but also reduce soil erosion and loss of nitrates and phosphorous, with lower cultivation and production costs, and without interfering with the growth of primary crops and their yield (Zanetti et al. 2021).

Furthermore, in northern latitudes, the growing season is too short to allow growing two crops in one season. Therefore, mixed cropping systems, either full-mix or relay crops, are the possible solutions to this environmental limitation. Recently, this type of system has also become popular in other areas in relation to constraints linked to water scarcity, weed and disease pressure, and soil limitations; thus growing two crops at the same time has become of interest among cultivators (Berti et al. 2015). In fact, several authors demonstrated that camelina could be successfully grown when mixed with lentils, peas, etc., without any negative impact on the growth and yield of the primary crop and without the need for any weedicide or weed control chemicals (Saucke and Ackermann 2006; Gollner et al. 2010; Leclere et al. 2019). In countries like France and Austria, mixed cropping is highly valuable for organic farming systems where camelina is grown together with soybean and lentils (Gollner et al. 2010). In the case of camelina and legume crops, the low vegetative growth at the early stage of the latter is compensated by the early vigour of the camelina, thus preventing any weed emergence (Zanetti et al. 2021). On the contrary, camelina mixed cropping with cereals and wheat resulted in low camelina yield, mainly due to strong competition with grass at early stages (Leclere et al. 2019). In addition, more research is required in this field to fully exploit this oilseed crop's potential.

Camelina seed and cake: Chemical characteristics

Camelina seeds have a lipid content ranging from 36.5 to 40.2% (Table 1). The fatty acid profile (Table 2) mainly comprises polyunsaturated fatty

Table 1. Chemical composition, anti-nutritional content, antioxidant profile, and energy content of camelina seed and cake

	Camelina sativa	
	seed[1–4]	cake[5–16]
Dry matter (%)	90.2 ± 4.63	92.9 ± 2.45
Crude protein (%)	25.9 ± 2.07	35.2 ± 2.95
Ether extract (%)	38.9 ± 1.26	13.7 ± 6.46
Crude fibre (%)	10.5 ± 2.08	12.4 ± 3.02
Ash (%)	4.25 ± 0.07	5.90 ± 0.58
Neutral detergent fibre (%)	–	38.5 ± 6.02
Acid detergent fibre (%)	–	20.3 ± 4.02
Glucosinolates (umol/g)	–	21.1 ± 3.90
Sinapine (g/kg)	–	2.26
α-Tocopherol (ug/g)	–	4.10 ± 1.56
γ-Tocopherol (ug/g)	410 ± 0.01	318 ± 327
Xanthophylls (ug/g)	41.3 ± 0.00	–
Phenolics (ug/g)	8 800 ± 0.00	4 409 ± 570
Flavonoids (ug/g)	–	14.8 ± 8.78
Energy (MJ/kg)	19.8 ± 8.04	16.9 ± 5.59

[1]Ciurescu et al. 2016; [2]Zajac et al. 2020; [3]Zajac et al. 2021; [4]Cherian and Quezada 2016; [5]Aziza et al. 2010; [6]Cherian et al. 2009; [7]Frame et al. 2007; [8]Nain et al. 2015; [9]Pekel et al. 2015; [10]Woyengo et al. 2016; [11]Bulbul et al. 2015; [12]Ryhanen et al. 2007; [13]Aziza et al. 2014; [14]Kakani et al. 2012; [15]Panaite et al. 2016; [16]Lolli et al. 2020

Data are presented as average ± standard deviation

Table 2. Fatty acid profile (% fatty acid methyl esters) of camelina seed, oil, and cake

	Camelina sativa		
	seed[1–2]	oil[3–4]	cake[5–15]
C16:0	6.27 ± 0.28	5.06 ± 0.00	7.98 ± 1.12
C18:0	2.20 ± 0.41	2.69 ± 0.00	2.55 ± 0.22
C21:0	–	–	1.51
SFA	9.04	11.0 ± 1.51	12.2 ± 2.11
C18:1	17.0 ± 0.76	15.7 ± 0.00	18.5 ± 3.33
C20:1	14.3 ± 1.82	14.6 ± 0.00	11.3 ± 2.23
C22:1	5.02	–	2.20 ± 0.57
MUFA	36.2	25.8 ± 11.2	36.3 ± 4.57
C18:2 *n*-6	18.9 ± 0.14	16.7 ± 0.00	23.9 ± 1.64
C18:3 *n*-3	33.3 ± 0.16	36.1 ± 0.00	30.7 ± 3.45
C20:2 *n*-6	1.47	–	1.57 ± 0.11
C20:3 *n*-3	–	–	1.08 ± 0.17
C20:3 *n*-6	–	1.51 ± 0.00	0.98 ± 0.11
C20:4 *n*-6	–	–	2.50
PUFA	55.6	54.6 ± 1.70	54.8 ± 1.46
n-3	33.8 ± 0.67	38.5 ± 0.00	34.8 ± 14.1
n-6	22.0 ± 0.41	14.9 ± 0.00	27.1 ± 3.69
n-6/*n*-3	0.65 ± 0.03	0.50 ± 0.15	0.83 ± 0.16

SFA = saturated fatty acids; MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids

[1]Ciurescu et al. 2016; [2]Cherian and Quezada 2016; [3]Jaskiewicz et al. 2014; [4]Pietas and Orczewska-Dudek 2013; [5]Aziza et al. 2010; [6]Cherian et al. 2009; [7]Juodka et al. 2018; [8]Nain et al. 2015; [9]Juodka et al. 2022; [10]Bulbul et al. 2015; [11]Aziza et al. 2014; [12]Cherian et al. 2009; [13]Kakani et al. 2012; [14]Panaite et al. 2016; [15]Lolli et al. 2020

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acids (PUFA) that account for 55% of total FA. The main FA of the *n*-3 series is the alpha-linolenic acid (C18:3 *n*-3), while the main FA of the *n*-6 series is the linoleic acid (C18:2 *n*-6): they account for 33% and 19% of total FA, respectively. Seeds have a favourable *n*-6/*n*-3 ratio, which is comprised of between 0.63 and 0.65. Like all members of the Brassicaceae family, also camelina seeds contain erucic acid (C22:1 *n*-9), but it was reported to be quite low (< 5%).

Furthermore, camelina seeds are a source of protein, ranging from 24.5 to 30 % of their weight (Table 1). Protein is rich in amino acids: arginine, leucine, valine, lysine, phenylalanine and isoleucine among the essential, and glutamic acid, aspartic acid, glycine and alanine among the non-essential ones.

Apart from PUFAs and protein, camelina seeds are also rich in antioxidants, such as phenolic acids, alpha-tocopherols, gamma-tocopherols, xanthophylls, phytosterols and flavonoids (Table 1), that stabilise oil and protect the unsaturated fatty acids from oxidation, thus prolonging the shelf-life. Such compounds are also responsible for the colour and taste of camelina oil. Furthermore, camelina seeds contain ash content ranging from 4.15 to 4.31% of their mass (Table 1), and the main minerals are reported to be a potassium, phosphorous, sulphur, magnesium, and calcium.

After the oil is extracted from seeds by various methods (i.e. solvent extraction, mechanical pressing, and supercritical CO_2 extraction) camelina cake is obtained. It is characterised by a high amount of dry matter (92.9%), an average 35% of protein, 5–28% of residual oil, and 5.90% ash. The high protein content and richness in essential amino acids make camelina cake comparable to soybean meal. Therefore, the rich and healthy nutritional profile, make camelina meal a high-quality by-product for potential use as livestock feed (Table 1).

Non-feed uses: Agrochemicals, biofuel, biopolymers, cosmetics and food

Camelina is an interesting oilseed plant with industrial potential also because it can have different non-feed applications: in fact, it can be exploited in the production of agrochemicals, biofuels, biopolymers, cosmetics and food.

Agrochemicals. Camelina oil is of great interest for the production of novel agrochemicals, even if research is still in its infancy. The reaction of camelina oil with quaternary ammonium hydroxides allowed the development of ammonium bio-ionic liquids (Klejdysz et al. 2016; Pernak et al. 2018), yielding between 86% and 93%. Such products were tested against storage pests such as granary weevil (*Sitophilus granaries*), khapra beetle and larvae (*Tribolium confusum*), as well as confused flour beetle (*Trogoderma granarium*), and as adjuvants for sulfonylurea herbicides: in both cases experimental results showed great activity, thus further highlighting the potential of camelina oil for these applications.

Biofuels. Biodiesel obtained from camelina showed better sustainability performance compared to mineral diesel fuel having lower carbon monoxide and toxic gases emission (Lebedevas et al. 2012). The fatty acid methyl esters obtained from camelina oil demonstrated to have characteristics comparable to rapeseed oil (Frohlich and Rice 2005) more sustainable environmental performance (lower land use) than oils obtained from soybean and rapeseed (Ciubota-Rosie et al. 2013; Bacenetti et al. 2017). Besides these positive properties, camelina biodiesel still has many drawbacks: it holds a high iodine value, high cloud filter pours point, high Conradson carbon residue, and it is highly prone to oxidation despite its natural content of antioxidants. One solution to partly overcome these drawbacks could be mixing 50% or 40% of pork lard or exhausted frying oil with camelina oil to attain standard iodine value, while commercially available antioxidants such as ionol could be added to have oxidation stability (Karcauskiene et al. 2014). Another strategy, probably the key point to practically allow camelina oil use as biofuel, could be the reduction of the high amount of unsaturated fat through genetic selection (Hernando et al. 2017).

Camelina oil adhesion properties are appropriate for the manufacturing of pressure-sensitive adhesives, thus becoming valuable for further uses, especially in combination with other epoxidised oils to produce biopolymers, resin (Kim et al. 2015), paints and varnishes (Nosal et al. 2016). In addition, epoxidised camelina oil is used for the synthesis of several types of hydrophilic-oil based monomers. Also, extending their work to investigate the poly(ethylene glycol) dimethacrylate (PEG) camelina oil in combination with different PEG copolymer systems protected with nanostructured

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polyhedral oligomeric silsesquioxane compounds (Balanuca et al. 2014, 2015).

Cosmetics. It is well known that vegetable oils have a major role in the cosmetic industry, being highly appreciated by consumers and thanks to their distinct natural properties (Arshad et al. 2022). Camelina oil is a rich source of antioxidants and displays high antioxidant activity, thus being formulated in many cosmetic products such as shampoos, creams, etc. Camelina can be used as a skin-conditioning agent-emollient or skin-conditioning agents-occlusive without any relevant toxicity risk (Ionescu et al. 2015; Quero et al. 2016; Burnett et al. 2017; Arshad et al. 2022). In addition, fatty acids derived from refined camelina oil were used in fragrances for cosmetic formulation (Project COSMOS 2020: https://cosmos-h2020.eu/#projectsum). These molecules may increase the economic diversification and sustainability of camelina oil in the market, even if specific research to this regard still needs to be carried out.

Food. As it has already been mentioned above, camelina oil is a great source of n-3 PUFA and, given the nutritional importance of this class of FA for human health. Furthermore, the study of Zubr (2009) showed that camelina oil could stimulate the metabolism of high-degree lipoproteins to form smaller-degree lipoproteins: this is due to the lipid-lowering activity of camelina oil, which is responsible for regulating the blood lipid metabolism, thus protecting, and reducing liver function and cardiovascular risks, respectively. For these properties, camelina oil has gained attention from the perspective of producing functional foods. Recently, Faustino et al. (2016) produced milk fat substitutes using camelina oil as a source of PUFA and manufactured a product which could mimic human milk fat to replace it for infants' nutrition. This was possible thanks to the acidolysis reaction between tripalmitin and free fatty acids of camelina oil with *Rhizopus oryzae* lipase as catalyst. Moreover, camelina oil was also employed in the manufacturing of margarine, mayonnaise, and ice cream, exploiting its favourable fatty acid composition but also taking advantage of its natural antioxidants present in camelina (Abramovic and Abram 2005).

Feed uses

Camelina sativa, also known as gold-of-pleasure or false-flax, is a crop that has gained interest as a potential source of animal feed. Several studies have been conducted to evaluate the potential application of camelina seeds, oil, or cake into animal feeding, as a sustainable alternative to common feedstuffs such as soybean meal or oil (Mondor and Hernandez-Alvarez 2021; Zanetti et al. 2021). The greatest potential in this sense is offered by the cake, which is the by-product of oil extraction, but it has an interesting nutritional profile, as it has previously been described. For this reason, research has been focusing on assessing the potential of this plant species in feed formulation intended for different animal species of economic interest, such as chicken, pig, rabbit, ruminants and fish (Peiretti et al. 2007; Paula et al. 2019; Mondor and Hernandez-Alvarez 2021; Zhu et al. 2021; Juodka et al. 2022). Besides the nutritional benefits of this feed source, which are mainly linked to the PUFA content and the valuable amino acid content and profile, research conducted up to now highlighted that some challenges associated with the use of camelina cake in animal feeding exist, as it will be explained in the next paragraph. For this reason, further research is necessary to make camelina cake a feasible feedstuff for food-producing animals.

DRAWBACKS AND POSSIBLE IMPROVEMENTS

The size of camelina seed is quite small. Therefore, a negative correlation between seed weight and both seed and oil yield were observed (Zanetti et al. 2017). Such characteristics of seeds make it less promising compared to other Brassicaceae family plants. In addition, camelina contains plant secondary metabolites, i.e., glucosinolates, phytic acid, sinapine, trypsin inhibitors, and condensed tannins. Glucosinolates are beta-thioglucoside N-hydroxysulfates with side chains and sulfur-linked beta-D-glucopyranose. The breakdown products nitriles, epithionitriles, isothiocynates, and thiocyanates are responsible for toxicity i.e., impairment of growth, thyroid function, fertility and reproduction, and irritation of gastrointestinal mucosa followed by necrosis (Alexander et al. 2008; Russo and Reggiani 2012). Phytic acid is the main organic form of the phosphorous present in plant seeds. It forms complexes with minerals, thus converting them into insoluble and biologically unavailable (Schlemmer et al. 2009).

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Sinapine is a choline ester of sinapic acid and has several undesirable properties, bitter-tasting compound, thus making it less palatable to animals, while its addition to poultry diets leads to a fishy odour or taste in the product (Butler et al. 1982). Condensed tannins have the ability to precipitate proteins, inhibit digestive enzymes, and thus decrease the absorption of vitamins and minerals. Tannins tend to form complexes with proteins and enzymes. These complexes directly or indirectly interfere with the activity of digestive enzymes such as trypsin and chymotrypsin. It also forms a complex with vitamin B_{12}, thus decreasing its absorption. However, they are also considered a health-promoting component in plant-derived foods and beverages as they have been shown to have antimicrobial, anticarcinogenic, and antimutagenic properties (Amarowicz et al. 2010).

The drawbacks mentioned above could be overcome using various improvement strategies such as artificial hybridisation, a simple way to obtain hybrid plants. Segregation generation could be handled using bulk breeding procedures or pedigree. The single-seed descent method was utilised in camelina breeding for rapid generation advance to reach homozygosity (Vollmann and Eynck 2015).

Besides hybridisation, mutation induction approaches have also been used to generate novel genetic variation. Seeds are treated either with ethyl methanesulfonate (EMS) or irradiated with gamma rays and were found to be suitable for inducing random mutations in plant genome mainly on guanine/cytosine to adenine/thymine transitions and it was found to modify FA composition effectively (Buchsenschutz-Nothdurft et al. 1998). The reduction in the sensitivity of camelina to acetolactate synthase inhibitor herbicides conferring resistance to imazethapyr, sulfosulfuron, and flucarbazone was observed when treated with EMS (Walsh et al. 2012). Moreover, the production of double haploids derived from other cultures or isolated microspores is another important technique for accelerating breeding programs (Vollmann and Eynck 2015).

Also, camelina and arabidopsis [*Arabidopsis thaliana* (L.) Heynh.] have a high sequence identity of genes. Therefore fully developed tools are available for breeding and trait improvement from genetic engineering (Vollmann and Eynck 2015). Genetic transformation based on agrobacterium-mediated floral dip transformation has been developed (Yuan and Li 2020) to improve seed, oil yield, drought resistance, etc. In addition, after EMS treatment of camelina, mutant seed lines with altered fatty acids composition can be detected, which provides an opportunity to target genes of interest with the help of CRISPR/Cas9 technology (Zanetti et al. 2021).

BROILER POULTRY SPECIES

Digestibility

Research conducted up to now, presented in Table 3, has highlighted that total tract apparent digestibility of nutrients can decrease when birds are fed diets containing camelina, especially its by-product.

Camelina seeds. The dietary inclusion of 15% camelina seed into the broiler chicken diets (Zajac

Table 3. Effect of the dietary inclusion of camelina by-products on apparent total tract digestibility (%) in broiler chicken

Species	Matrix	Inclusion (%)	Dry matter	Organic matter	Crude protein	Ether extract	Energy	References
Chicken	control	0	75.6 ± 4.13	81.4 ± 0.85	85.8 ± 2.90	73.4 ± 3.15	80.4 ± 5.50	1–5
	seed	15	83.6	87.5*	78.3*	73.5	86.2	1!
			83.0	84.0	78.9	64.5*	78.2*	2
	cake	8, 16, 24	61.6**	–	54.5**	42.0**	62.1**	3
		10, 20	60.4**	–	–	–	67.1**	4
		3, 6, 9, 12, 15	65.1**	–	–	–	67.9**	5

Control = mean value of all control diets ± standard deviation

[!]In study 1, camelina seeds were micronised; [1]Zajac et al. 2021; [2]Zajac et al. 2020; [3]Orysachak et al. 2020; [4]Pekel et al. 2015; [5]Thacker and Widyaratne 2012

*$P < 0.05$; **$P < 0.01$ vs control within study

et al. 2020) showed to reduce fat digestion efficiency in the grower and finisher phases, while it reduced energy digestibility in the only grower phase; this result was mainly linked with the presence of high content of non-starch polysaccharides (NSP, mainly water soluble) in camelina seeds. The presence of a high amount of water-soluble NSP is associated with increased digesta viscosity, which plays a key role in the negative effect on the digestibility of all nutrients, especially fat (Amerah et al. 2014). The breakdown of anti-nutritional compounds forms complexes with available nutrients and digestive enzymes present inside the gastrointestinal tract of a bird, therefore reducing their solubility, bioavailability, and activity (Zajac et al. 2020). However, Woyengo et al. (2016) indicated that it is possible to reduce the effect of glucosinolates and trypsin inhibitors through the supplementation of multi-enzyme (Superzyme OM, Canadian Bio-System Inc., Calgary, AB, Canada; one g/kg); this increased the digestibility of most of the amino acids and metabolisable energy. Similarly, Zajac et al. (2021) micronised camelina seed with an infrared radiation generator (ESC-1 infrared illuminator panel) that improved seed composition and inactivated anti-nutritional compounds. Moreover, infrared-irradiated camelina seeds were also lower in ash and crude fibre content, whereas improved the dry matter, crude protein, and ether extract contents were enhanced. The inclusion (15%) of these micronised seeds into the broiler chicken diets significantly increased the nutrient digestibility, specifically for crude protein and organic matter, compared to the control group.

Camelina cake. The dietary inclusion of a 3% camelina cake into the diet for broiler chickens showed not to affect the nutrient digestibility (Thacker and Widyarante 2012). However, when the inclusion levels increased to 6–15% (Thacker and Widyarante 2012), 10–20% (Pekel et al. 2015), and 8–24% (Oryschak et al. 2020), the apparent nutrients digestibility: this result could be attributable to the presence of non-starch polysaccharides in the camelina cake, responsible for increasing the digesta viscosity and thus resulting in lowering nutrient absorption (Thacker and Widyarante 2012; Pekel et al. 2015; Oryschak et al. 2020).

Research conducted until now, yet limited, demonstrated that including a significant level of camelina seeds or cake into the broiler poultry diets can negatively influence nutrient absorption and utilisation by increasing digesta viscosity. As discussed earlier (section Drawbacks and possible improvements), camelina by-products contain anti-nutritional compounds and high fibre amount (Table 1) that negatively affect broiler chickens' nutrient and energy digestibility. However, it was also demonstrated that diets containing either infrared irradiated camelina seeds or cake supplemented with the multi-enzyme can reduce the digesta viscosity in the gastrointestinal tract of broiler chickens, ultimately improving nutrient digestibility. Despite this, further research is required to understand better the optimal ways to incorporate camelina by-products into broiler poultry diets to maximise their nutritional benefits while minimising any negative effects.

Live performances

Different dietary camelina products and different levels of their inclusion into the diet of different broiler poultry species determined inhomogeneous effects on the growth performance (Table 4), but without affecting the mortality rate.

Camelina seeds. The inclusion of 5% or 10% camelina seed into the broiler chickens' diet for 42 days of feeding had no effect on the growth performance (Ciurescu et al. 2016) or resulted in higher daily weight gain to the control (Ciurescu et al. 2007) while ensuring a similar feed conversion ratio (FCR). The 15% dietary inclusion provided the best outcomes for FCR and mortality in the camelina-fed group compared to the group which was fed a conventional diet (Zajac et al. 2020). Furthermore, when camelina seeds were incorporated (15%) into chickens' diet after being infrared irradiated and micronised (Zajac et al. 2021), they showed to positively affect daily weight gain, FCR, and mortality of chickens, especially during the finisher phase.

The result available up to now seems to indicate that camelina seeds have the potential to provide a range of nutritional benefits and to positively impact live performance of broiler chickens.

Camelina oil. It is well established that camelina oil contains a low or negligible amount of anti-nutritional compounds compared to the seed or cake; therefore, it was not surprising to depict that the dietary inclusion (1.43–6%) of camelina oil into the broiler chickens' diet did not have any

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Table 4. Effect of the dietary inclusion of camelina by-products on broiler poultry growth performance

Species	Matrix	Feeding (days)	Inclusion (%)	Weight gain (g/day)	FI (g/day)	FCR	Mortality (%)	References
Chicken	control		0	56.6 ± 16.6	100 ± 31.3	1.74 ± 0.22	2.40 ± 0.93	1–13
	seed	35	10	49.6*	101	2.09	0.50	1
		21	15	44.1	122	1.93*	2.12*	2!
		21	15	43.9	81.7	1.86*	2.14*	3
		42	5, 10	56.1	103	1.87	1.25	4
	oil	42	2.5	60.2	104	1.75	1.92	4
		24	1.43, 2.17	75.8	125	1.64	–	5
		49	3, 6	50.2	–	1.66	2.49	6
		35	6.9, 4.1	58.0	94.0	1.62	–	7
		21	4	87.3	144	1.57	1.31	8
	cake	21	10	82.6	141	1.65	1.74	8
		42	2.5, 5, 10	49.1**	83.9	1.85	–	9
		37	5, 10	36.0**	69.0*	1.90**	1.50	10
		21	10	29.2**	43.9**	1.54**	–	11
		7	10, 20	56.1**	95.7**	1.70**	–	12
		28	3	55.1	120	2.16	–	13
Turkey	control		0	29.9 ± 0.19	48.3 ± 0.12	1.68 ± 0.06	–	14
	oil	28	100	29.1	49.0	1.68	–	14
	cake	28	5, 15	28.2	48.7	1.73	–	14
		28	5, 15, 20	24.9	42.4**	1.86**	–	
Duck	control		0	55.1	163	3.01	–	15
	cake	49	15, 20	52.6	148*	2.93	–	15
Quail	control		0	6.07 ± 1.31	23.2 ± 7.90	3.87 ± 0.63	0.83	16–17
	cake	35	5, 10, 15, 20	5.16	18.1	3.50*	–	16
		21	15	6.81*	29.3*	4.56**	1.11	17

FCR = feed conversion ratio; FI= feed intake

[!]In study 2, camelina seeds were micronised; [1]Ciurescu et al. 2007; [2]Zajac et al. 2021; [3]Zajac et al. 2020; [4]Ciurescu et al. 2016; [5]Jaskiewicz et al. 2010; [6]Pietras and Orczewska-Dudek 2013; [7]Jaskiewicz et al. 2014, [8]Orczewska-Dudek and Pietras 2019; [9]Aziza et al. 2010; [10]Ryhanen et al. 2007; [11]Pekel et al. 2009; [12]Pekel et al. 2015; [13]Untea et al. 2019; [14]Frame et al. 2007; [15]Juodka et al. 2022; [16]Bulbul et al. 2015; [17]Cullere et al. 2023

*P < 0.05; **P < 0.01 vs control within study

Data are presented as mean value of species-specific control diet ± standard deviation

significant effect on the live performances compared to those provided by conventional oil sources (Pietras and Orczewska-Dudek 2013; Jaskiewicz et al. 2014; Ciurescu et al. 2016; Orczewska-Dudek and Pietras 2019).

Similarly, a study by Frame et al. (2007) demonstrated that the complete replacement (100%) of vegetable oil with camelina oil (2.2% inclusion level) did not significantly affect the daily weight gain and FCR in turkey poults compared to the group fed a conventional diet. In the case of broiler quails, a study by Pellattiero et al. (2021) indicated that the complete replacement (100%) of soybean oil with camelina oil (1.60% inclusion level) in the broiler quails diet showed an increase in growth and better FCR throughout the experimental study.

Camelina cake. The presence of anti-nutritional factors in camelina cake, being more concentrated in the latter compared to the seeds, makes its application into feed formulations for poultry species, particularly challenging. In fact, experimental results show contradictory outcomes: a study by Aziza et al. (2010) showed that the dietary inclusion (2.5%) of camelina cake into the broiler chickens' diets significantly reduced daily weight gain compared to the control group. Oppositely, 3% inclusion did not affect the live performances in broiler chickens and remained comparable to the control (Untea et al. 2019). A higher inclusion of camelina cake (5%) improved daily weight gain (Aziza et al. 2010), feed intake, as well as FCR, especially in male birds (Ryhanen et al. 2007). The 10% inclusion level into broiler chicken diets provided alternate results: Orczewska-Dudek and Pietras (2019) did not find differences in live performance, whereas Ryhanen et al. (2007), Pekel et al. (2009), Aziza et al. (2010), and Pekel et al. (2015) observed significantly lower performance for daily weight gain, feed intake, and FCR. As expected, increasing the inclusion level (up to 20%) of camelina meal into the broiler chickens' diet made even worse growth, feed intake, and FCR (Pekel et al. 2015).

When different poultry species than chicken were analysed, the pattern did not change: in the case of turkey poults, Frame et al. (2007) observed that increasing the inclusion level (5–20%) of camelina cake into their diet negatively affected the daily weight gain, reduced feed intake. Furthermore, a higher feed intake was recorded for the group containing 15–20% camelina cake, and a higher FCR was recorded for birds fed 20% camelina cake in their diet.

As for ducks, including camelina cake up to 15–20% did not affect the daily weight gain and FCR. However, a significant reduction in feed intake was recorded compared to the control groups (Juodka et al. 2022), thus highlighting a further possible issue with palatability.

In the case of broiler quails, an inclusion rate of 10% did not affect the live performances, which remained in line with the groups fed the control diet. However, when increasing inclusion levels of camelina cake (15–20%), FCR consistently increased thus (Bulbul et al. 2015). Similar outcomes were also reported by Cullere et al. (2023), where a dietary inclusion with 15% camelina cake obtained from three different varieties (Calena: commercial, Ala: reduced glucosinolates, and Pearl: low linoleic acid) was tested: all varieties generated unsatisfactory live performance compared to the control group, especially Calena group whose FCR was the highest.

Overall, experimental data highlighted that using different camelina products determines different outcomes on live performance (i.e. weight gain, feed intake, and FCR) in different poultry species. Other factors playing a relevant role on live performance are the inclusion level, feeding duration, and camelina variety. However, a common finding of all studies is that high dietary incorporation of camelina cake challenges birds' live performance, thus indicating that a 10% threshold seems desirable. The latter inclusion level proved to be appropriate also for camelina seeds. For higher levels (> 10%), instead, it would be required to include supplements, such as copper or enzymes, or to micronise camelina seed or cake to reduce the levels of anti-nutritional factors or crude fibre content, ultimately ensuring acceptable live performance. In these regards, however, further research is necessary to understand and optimise the use of camelina cake and seed in broiler diets to maximise the positive effects on the live performance parameters.

Conversely, the inclusion of camelina oil in broiler diets showed to improve weight gain, feed intake and FCR, especially when used as a replacement for other vegetable oils in the diet, thus making it suitable and even beneficial for poultry species.

Carcass traits

Experimental data highlight that the use of camelina-derived products in the diet for broiler poultry species can have a relevant effect on carcass traits, as it can be observed in the results presented in Table 5.

Camelina seeds. The dietary inclusion of either 5% or 10% (Ciurescu et al. 2016) or 15% (Zajac et al. 2020) of camelina seeds did not affect broiler chickens' carcass traits compared to the groups fed the control diet. This may be attributable to the low concentration of anti-nutritional compounds in camelina seeds or the experiments' short feeding period (21 days).

Camelina oil. Similar to the findings on camelina seeds, when broiler chickens were fed with diets containing camelina oil at inclusion levels comprised between 2.5% and 6%, results on carcass traits were comparable to those of the control groups (Pietras and Orczewska-Dudek 2013; Ciurescu et al. 2016; Orczewska-Dudek and Pietras 2019). Such findings were expected as camelina oil does not contain anti-nutritional compounds that can negatively affect carcass traits.

Camelina cake. As it was highlighted for live performance, being intimately connected, in the case of camelina cake, experimental outcomes did not give univocal indications: some studies indicated

Table 5. Effect of the dietary inclusion of camelina by-products on carcass traits of broiler poultry

Species	Matrix	Feeding (days)	Inclusion (%)	Slaughter weight (g)	Carcass weight (g)	Carcass yield (%)	Leg weight (g)	Leg yield (%)	Breast weight (g)	Breast yield (%)	Abdominal fat (%)	References
Chicken	control		0	2 028 ± 752	1 537 ± 634	71.6 ± 3.81	313 ± 120	22.5 ± 6.67	371 ± 135	26.7 ± 4.52	3.78 ± 6.32	1–6
	seed	21	15	–	–	–	149	–	359	–	7.46	1
		42	5, 10	–	–	73.4	396	–	331	–	0.78	2
	oil	42	2.5	–	–	74.2	404	–	336	–	1.02	2
		49	3, 6	2 696	1 986	73.6	307	15.5	390	19.7	0.98	3
		21	4	2 602	1 888	72.5	410	21.7	542	28.7	1.58	4
	cake	21	10	2 473	1 799	72.7	387	21.5	470	26.1*	1.52	4
		21	10	621*	399*	64.2	126*	31.6	120*	30.1	–	5
		42	2.5, 5, 10	–	1 512	–	–	–	–	–	2.19	6
Duck	control		0	2 731	1 858	68.0	234	12.6	188	10.1	1.35	7
	cake	49	15, 20	2 527	1 665**	66.0**	230	13.8	151	9.09	1.15	7
Quail	control		0	255	146 ± 32.7	66.5	41.3	24.4	55.8	32.9	–	8–9
	cake	35	5, 10, 15, 20	–	121	–	–	–	–	–	–	8
		21	15	249*	165*	66.6	40.06	24.3	55.8	32.9	–	9

[1]Zajac et al. 2020; [2]Ciurescu et al. 2016; [3]Pietras and Orczewska-Dudek 2013; [4]Orczewska-Dudek and Pietras 2019; [5]Pekel et al. 2009; [6]Aziza et al. 2010; [7]Juodka et al. 2022; [8]Bulbul et al. 2015; [9]Cullere et al. 2023

*$P < 0.05$; **$P < 0.01$ vs control within study

Data are presented as mean value of species-specific control diet ± standard deviation

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that the inclusion of 2.5–10% camelina cake did not affect the carcass traits of the broiler chickens (Aziza et al. 2010; Orczewska-Dudek and Pietras 2019), whereas a study by Pekel et al. (2009) indicated the dietary inclusion of 10% camelina cake into the broiler chicken diets negatively affected carcass traits, which is linked to the results on live performance (Table 4): slaughter weight, carcass weight, leg weight as well as breast weight were significantly lower compared to the group-fed control diet.

In the case of duck, the dietary inclusion of either 15% or 20% camelina cake did not alter the carcass traits, except for carcass weight and yield (Juodka et al. 2022). The presence of anti-nutritional compounds can negatively affect nutrient absorption, thus resulting in reduced growth, which is directly linked to carcass traits, including proportions, yields, and quality.

When camelina cake was tested in broiler quails (Cullere et al. 2023) results suggested that a 15% dietary inclusion of commercially available camelina (i.e., Calena) is not ideal since it decreased the slaughter and carcass weights compared to the control. However, when improved camelina varieties (low glucosinolates and low linoleic acid) were considered, negative effects on carcass traits were not observed.

The use of camelina-derived products in broiler diets had wide-ranging effects on carcass traits, depending on the same factors highlighted for live performance (level of inclusion and feeding period). Moreover, most of the findings on carcass traits were directly dependent on nutrient absorption and growth, as a result of diets containing camelina seeds or cake. For these reasons, it is recommended that high doses of camelina-derived products in poultry diets (seed or cake) are avoided in the starter phase, as young birds are particularly sensitive to the presence of anti-nutritional compounds (Aziza et al. 2010). Differently, the inclusion of the oil fraction in the diet of different poultry species did not pose any particular issue.

Meat quality

Proximate composition. In Table 6, the literature findings regarding the effects of the dietary inclusion of camelina-derived products on the proximate composition of either breast or leg meat from different broiler poultry can be found.

Camelina seeds. Including 5–10% of camelina seeds into the broiler chicken diets did not affect the chemical composition of breast meat (Ciurescu et al. 2016). However, increasing the inclusion level to 15% significantly reduced the lipid and ash content of breast meat compared to the control group (Zajac et al. 2020). In the same study, authors also

Table 6. Effect of the dietary inclusion of camelina by-products on proximate composition (%) of chicken breast and leg meat

Species	Cut type	Matrix	Feeding (days)	Inclusion (%)	Water	Protein	Lipids	Ash	References
Chicken	leg	control		0	73.9 ± 0.00	17.6 ± 0.00	7.50 ± 0.00	1.03 ± 0.00	1–4
	breast	control		0	75.1 ± 0.81	22.8 ± 1.29	1.09 ± 0.22	1.19 ± 0.00	1–4
	leg	seed	21	15	75.6	18.3	5.10*	1.01	1
	breast	seed	21	15	76.6	21.2	1.08*	1.12*	1
			42	5, 10	69.8	21.8	2.30	–	2
		oil	42	2.5	69.6	20.9	2.21	–	2
			49	3, 6	74.9	23.7*	0.81	–	3
			21	4	74.8	23.5	1.10	–	4
		cake	21	10	74.1	23.8	1.15	–	4
			28	3	–	21.1	1.19	1.20	5
Quail	breast	control		0	75.1	21.7	2.07	1.37	6
		cake	21	15	75.5*	21.6	1.65**	5.66	

[1]Zajac et al. 2020; [2]Ciurescu et al. 2016; [3]Pietras and Orczewska-Dudek 2013; [4]Orczewska-Dudek and Pietras 2019; [5]Untea et al. 2019; [6]Cullere et al. 2023

*$P < 0.05$; **$P < 0.01$ vs control within study

Data are presented as mean value of species-specific control diet ± standard deviation

observed lower lipid content in leg meat compared to the control group. As it was stressed for live performance, the inclusion of camelina seeds (> 10%) in poultry diets showed to increase digesta viscosity, playing a key role in nutrient digestibility, particularly fat (Amerah et al. 2014), therefore possibly explaining why lower lipid contents were observed in the obtained chicken breast and leg meat.

Camelina oil. The dietary inclusion of either 2.5% (Ciurescu et al. 2016) or 4% (Orczewska-Dudek and Pietras 2019) camelina oil into broiler chickens' diet did not affect the chemical composition of breast meat compared to the group fed a control diet. Though, the inclusion of 3% camelina oil into the broiler chickens' diet displayed higher protein content in breast meat, whereas inclusion at 6% did not affect the protein content of breast meat. In the mitochondria, polyunsaturated fatty acids (PUFA) are involved in the induction of uncoupling proteins. This mechanism could reduce the dietary energy in animals fed on a diet rich in *n*-3 PUFA (i.e. camelina), thus making energy preferably exploited for protein deposition (Pietras and Orczewska-Dudek 2013). This mechanism could hypothetically explain the findings regarding the 3% dietary incorporation of camelina oil but not those of the 6%, thus requiring further insights.

Camelina cake. The dietary inclusion of a 3% (Untea et al. 2019) and a 10% (Orczewska-Dudek and Pietras 2019) camelina cake in the diets for broiler chickens, provided breast meat with a chemical composition similar to the control group. On the contrary, in the case of broiler quails, Cullere et al. (2023) observed that the dietary inclusion of 15% camelina meal can influence the chemical composition of breast meat in quails. Higher water content and lower lipids were recorded for the group fed commercially available camelina line, i.e., Calena, compared to the control group. In contrast, the other two groups with improved camelina varieties (low glucosinolates and low linoleic acid) displayed intermediate values.

From the limited literature data available up to now, it can be stated that the use of camelina by-product in broiler diets can modify the proximate composition of meat, especially when the dietary incorporation exceeds 10%. Also, in the case of meat proximate composition, other factors such as feeding duration, camelina variety, and processing techniques should be considered as they are undoubtedly involved in determining the final outcomes.

Fatty acids

The Food and Agriculture Organization (FAO) of the United Nations recommends reducing the daily consumption of saturated fatty acids (SFA) for a healthy diet in this sense, the fatty acid profile and content of human food, in this case meat, plays an important role.

The oil fraction of the *Camelina sativa* (Table 2) is rich in monounsaturated (MUFA) and polyunsaturated (PUFA) fatty acids at levels of about 30% and 55% of total FA, respectively. Therefore, the dietary inclusion of camelina into broiler poultry diets offers the opportunity to change FA proportions of meat, leading to a reduction in SFA and enhancement of unsaturated FA (UFA). The effect of the dietary inclusion of camelina-derived products on the FA profile of different poultry meat cuts is presented in Tables 7 and 8.

Camelina seeds. The inclusion of 5–10% camelina seeds affected the total *n*-6 and total *n*-3 PUFA in the chicken breast meat. It reduced the SFA content, particularly the stearic acid (C18:0). These results were observed due to the high proportions of alpha-linolenic acid (ALA: C18:3 *n*-3), eicosapentaenoic acid (EPA: C20:5 *n*-3), arachidonic acid (AA: C20:4 *n*-6), docosapentaenoic acid (DPA: C22:5 *n*-3), and docosahexaenoic acid (DHA: C22:6 *n*-3) in chicken breast meat. A reduction in total *n*-6 PUFA and an increment in total *n*-3 PUFA were observed on increasing the inclusion level. The magnitude of the change in the proportions of FA was amplified with increasing camelina seed inclusion level (Ciurescu et al. 2016). The *n*-3 FA are key players for proper foetal development, including neuronal, retinal, and immune functions.

Camelina oil. Like camelina seed, Ciurescu et al. (2016) also demonstrated the positive effect of the oil fraction at a 2.5% inclusion level on the total *n*-6 and *n*-3 PUFA in breast meat. A higher proportion of ALA, EPA, AA, DPA, and DHA, and a lower proportion for C18:0 was observed in chicken breast meat. Inclusion at a 3% dose (Pietras and Orczewska-Dudek 2013) positively influenced the main FA classes (i.e., total MUFA, total PUFA, total *n*-6, total *n*-3, and *n*-6/*n*-3 ratio) too. As expected, higher inclusion levels of camelina oil in the diet determined similar yet more positive findings, such as 4% (Orczewska-Dudek and Pietras 2019) and 6% (Pietras and Orczewska-Dudek 2013) levels. Also, the complete replacement of soybean oil with

Table 7. Effect of the dietary inclusion of camelina by-products on main fatty acid classes (% fatty acid methyl esters), pH and TBARs of broiler poultry breast and leg meat

Species	Matrix	Cut type	Feeding (days)	Inclusion (%)	SFA	MUFA	PUFA	n-6	n-3	n-6/n-3	pH	TBARs[†]	References
Chicken	control	breast		0	29.5 ± 3.32	39.7 ± 5.79	30.0 ± 7.38	25.8 ± 7.38	3.85 ± 1.80	8.83 ± 7.31	5.95 ± 0.01	0.39 ± 0.05	1–8
		leg			29.6 ± 7.39	44.7 ± 2.05	21.6 ± 8.20	18.0 ± 6.72	3.66 ± 1.49	8.23 ± 5.32	–	–	
		abdominal fat			24.0 ± 0.98	50.2 ± 0.00	26.4 ± 0.00	23.5 ± 0.00	2.93 ± 0.00	8.02 ± 7.25	–	–	
	seed	breast	42	5, 10	–	–	37.1	29.1*	7.93**	3.67	5.98	–	1
	oil	breast	42	2.5	–	–	37.3	28.9*	8.47**	3.41	6.02	–	1
			49	3, 6	30.4*	28.1**	41.6**	26.4*	12.5**	2.21**	–	–	2
			21	4	31.8	36.5**	31.7**	20.8	10.1**	2.06**	–	0.36	3
			35	6.9, 4.1	24.6	–	–	–	–	4.78**	–	–	4
		leg	35		23.2	–	–	–	–	2.79**	–	–	4
		abdominal fat	35		24.3	–	–	–	–	2.63**	–	–	4
	cake	breast	21	10	28.7	39.7**	31.7**	21.9	8.94**	2.46**	–	0.35	3
			42	8, 16, 24	32.8**	39.1**	21.6	18.3**	3.80**	2.33**	–	–	5
			28	3	30.3**	–	–	27.2	1.63**	16.7**	–	0.06	6
			42	2.5, 5, 10	29.5	33.3**	37.5	33.7**	3.80**	9.13**	–	–	7
		leg	42	8, 16, 24	36.1	41.9*	22.0	14.8	7.23**	2.46**	–	–	5
			37	5, 10	23.6**	41.4**	31.6**	23.8	7.82**	3.04**	–	–	8
		abdominal fat	21	3, 6, 9, 12, 15	20.9	43.5**	35.6**	–	8.42**	–	–	–	9
Duck	control	breast		0	31.0	51.7	15.5	12.8	2.67	5.02	–	–	10
		leg			28.6	56.0	14.2	12.0	2.17	5.54	–	–	
	cake	breast	49	15, 20	31.6	49.5	17.4	12.8	4.53**	2.83**	–	–	10
		leg	49	15, 20	30.9**	51.9**	16.7**	12.0	4.67**	2.57**	–	–	
Quail	control			0	–	–	–	–	–	–	5.64	0.94	11–12
	cake	breast	35	5, 10, 15, 20	–	–	–	–	–	–	5.66*	0.89	11–12

MUFA = monounsaturated fatty acids; PUFA = polyunsaturated fatty acids; Ref = references; SFA = saturated fatty acids

[†]Thiobarbituric acid reactive substances (malondialdehyde/kg of meat); [1]Ciurescu et al. 2016; [2]Pietras and Orczewska-Dudek 2013; [3]Orczewska-Dudek and Pietras 2019; [4]Jaskiewicz et al. 2014; [5]Nain et al. 2015; [6]Untea et al. 2019; [7]Aziza et al. 2010; [8]Ryhanen et al. 2007; [9]Thacker and Widyaratne 2012; [10]Juodka et al. 2018; [11]Bulbul et al. 2015; [12]Cullere et al. 2023

*$P < 0.05$; **$P < 0.01$ vs control within study

Data are presented as mean value of species-specific control diet ± standard deviation

Table 8. Effect of the dietary inclusion of camelina by-products on fatty acid profile (% fatty acid methyl esters) of broiler poultry breast and leg meat

Species	Cut type	Matrix	Feeding (days)	Inclusion (%)	C16:0	C18:0	C16:1	C18:1 *n*-9	C18:2 *n*-6	C18:3 *n*-3	C20:4 *n*-6	C20:2 *n*-6	C20:5 *n*-3	C22:5 *n*-3	C22:6 *n*-3	Ref
Chicken	breast	control		0	20.7 ± 1.08	7.88 ± 2.41	2.59 ± 1.64	34.8 ± 5.51	22.3 ± 8.61	1.26 ± 0.80	4.61 ± 2.55	0.67 ± 0.30	0.45 ± 0.25	0.86 ± 0.08	0.87 ± 0.92	1–9
	leg				22 ± 5.02	5.29 ± 0.84	6.65 ± 4.45	35.8 ± 3.71	22.7 ± 12.6	2.82 ± 1.22	0.96 ± 0.27	0.23 ± 0.00	0.03 ± 0.00	0.27 ± 0.00	0.41 ± 0.00	
	abdominal fat				18.7 ± 0.71	4.48 ± 0.23	4.55 ± 0.00	40.2 ± 6.54	29.0 ± 8.51	2.46 ± 0.66	0.28 ± 0.00	–	–	–	–	
	breast	seed	42	5, 10	22.1	8.24*	–	29.9*	21.9	3.30**	5.61*	0.57	1.12*	1.14*	2.27**	1
		oil	42	2.5	22.2	7.43*	–	30.4*	21.8	3.70**	5.58*	0.55	1.19*	1.12*	2.32**	1
			49	3, 6	20.5	9.49*	1.09	26.4**	20.8	8.23**	5.56	–	1.62**	–	2.66*	2
			21	4	21.4	8.63	1.81	34.6**	17.6	8.07**	3.04*	–	1.00**	–	1.02	3
			35	6.9, 4.1	21.7	3.31**	–	50.0**	19.4**	4.12**	–	–	–	–	–	4
	leg		35		17.9**	4.61	–	38.6	28.2**	9.96**	–	–	–	–	–	4
	abdominal fat		35		18.5	5.15**	–	42.3**	20.5**	7.78**	–	–	–	–	–	4
	breast	cake	21	10	19.6	7.56	1.57	38.0**	18.9**	7.26**	2.91*	–	0.71		0.98	3
			42	8, 16, 24	19.4**	7.17	4.10**	31.7**	14.7**	5.33**	1.83	0.69*	0.10	1.38**	1.37	5
			28	3	21.2	7.12**	2.47	36.4	25.2	0.77**	1.16	0.19*	0.32		0.08	6
			42	2.5, 5, 10	20.3	8.04	3.74*	28.9**	24.8	1.81**	5.51*	0.75	0.26	0.99	0.72	7
	leg		42	8, 16, 24	25.2	5.17	7.57*	31.5	13.0*	6.00**	0.84	0.36**	0.03	0.49*	0.50	5
			37	5, 10	16.4**	6.16	2.60**	37.7**	21.7*	7.15**	1.05	–	–	–	–	8
	abdominal fat		21	3, 6, 9, 12, 15	15.8	4.71	3.40	38.0**	26.4	8.28**	0.38	0.38**	0.07	–	–	9
Duck	breast	control		0	22.7	7.32	2.70	45.4	9.96	1.80	2.00	0.21	0.20	0.32	0.27	10
	leg				21.4	6.34	3.48	48.9	10.1	1.57	1.29	0.17	0.11	0.28	0.19	
	breast	cake	49	15, 20	23.2	7.31	2.78	42.5	10.2	3.29**	1.62	0.37	0.28	0.41	0.4	
	leg		49	15, 20	22.7**	6.71	3.15	44.1**	10.4**	3.80**	0.93	0.35**	0.17	0.32	0.25	

Ref = references

[1]Ciurescu et al. 2016; [2]Pietras and Orczewska-Dudek 2013; [3]Orczewska-Dudek and Pietras 2019; [4]Jaskiewicz et al. 2014; [5]Nain et al. 2015; [6]Untea et al. 2019; [7]Aziza et al. 2010; [8]Ryhanen et al. 2007; [9]Thacker and Widyaratne 2012; [10]Juodka et al. 2018

*$P < 0.05$; **$P < 0.01$ vs control within study

Data are presented as mean value of species-specific control diet ± standard deviation

camelina oil (6.91%) provided similar outcomes, with an observed reduction in abdominal fat compared to the control group (Jaskiewicz et al. 2014).

Camelina cake. Despite the fact that the camelina cakes contains only a residual fraction of oil, experimental findings seem to indicate that also this by-product offers the opportunity to improve meat healthiness, thus further encouraging to exploit the cake fraction into poultry nutrition. Available data (Ryhanen et al. 2007; Nain et al. 2015) showed that the dietary inclusion of camelina cake into chickens' diet (5–24%) had a positive effect on lowering the total SFA in chicken breast and leg meat, mainly thanks to a reduction in the proportion of palmitic acid (C16:0).

A similar trend was also observed for total MUFA, where the total content of MUFA decreased by increasing the dietary inclusion (2.5–24%) of camelina cake. The decrease in MUFA was influenced mainly by the reduction of oleic acid (C18:1 *n*-9) in chicken breast and leg meat (Ryhanen et al. 2007; Aziza et al. 2010; Nain et al. 2015; Orczewska-Dudek and Pietras 2019; Untea et al. 2019) as well as in abdominal fat (Thacker and Widyaratne 2012) compared to the control group.

In the case of PUFA the inclusion 2.5–24% camelina cake linearly increased the total PUFA in chicken breast and leg meat. Where total *n*-3 PUFA content in chicken breast and leg meat significantly increased. These changes were mostly influenced by the increase in the proportion of ALA in chicken breast and leg meat (Ryhanen et al. 2007; Aziza et al. 2010; Nain et al. 2015; Ciurescu et al. 2016; Orczewska-Dudek and Pietras 2019; Untea et al. 2019) as well as in abdominal fat (Thacker and Widyaratne 2012) compared to the groups fed a control diet. Inclusion at a lower level, i.e., 2.5%, displayed the least increase in ALA, 1.78 and 1.32 times for breast and leg meat, respectively (Aziza et al. 2010). Conversely, Ryhanen et al. (2007) indicated that increasing the inclusion level (5–10%) can increase ALA content in breast and leg meat by 3.90 and 4.37 times, respectively. Moreover, the inclusion of camelina meal up to 24% resulted in 3.07- and 7.56 times higher ALA in breast and leg meat, respectively (Nain et al. 2015). Long chain fatty acids, such as EPA and DHA, are very important in human nutrition. Humans can convert short-chain *n*-3 fatty acids, but the efficiency is limited: < 1% in infants and ageing people and < 5% in adult humans. However, birds such as geese, ducks, etc., have been reported to convert short-chain to long-chain *n*-3 PUFA more efficiently with the help of desaturase and elongase in the liver (Nain et al. 2015; Juodka et al. 2018).

When ducks were studied, the dietary inclusion of a 15–20% camelina cake improved the total *n*-3 content of the breast meat as well as the ratio *n*-6/*n*-3, but the main FA classes remained unaffected. In the case of leg meat, however, the effect was much more pronounced, being all the main FA classes affected by the dietary inclusion of camelina cake. The different magnitude of the observed effect in breast and leg meat cuts is simply attributable to the different absolute fat contents of the meat portions. The above-mentioned positive effects of camelina cake on meat FA profile and content are attributable to the fact that birds are monogastric animals, thus effectively incorporating dietary FA into their body and that they have a remarkable lipogenic activity: FA synthesised in the liver are effectively transported to different body tissues such as adipose, cardiac, and skeletal muscles (Juodka et al. 2018).

Despite the intense changes in meat FA profile and contents, the research highlighted that, overall, the dietary inclusion of different camelina products did not affect the pH and lipid oxidation extent in the meat of broiler chickens (Ciurescu et al. 2016; Orczewska-Dudek and Pietras 2019; Untea et al. 2019), ducks (Juodka et al. 2018), and quail (Cullere et al. 2023).

Adding camelina-derived products to the diet of broiler chickens increased the concentration of *n*-3, including eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), as well as reducing the SFA in the meat cuts and abdominal fat. The intensity of the effect increased was amplified with increasing inclusion level (2.5–24%). These positive changes in the fatty acid profile of the meat could have potential health benefits for consumers, as *n*-3 FA are associated with a wide range of health benefits, including reducing the risk of cardiovascular disease, inflammation, and certain types of cancer. It is important to note that the optimal level to achieve these beneficial changes in the FA profile of the meat is still being researched, the latter being also in function of the target poultry species as well as to non-animal factors such as processing, and storage conditions which can affect the quality of the camelina products and, as a consequence the quality of meat. Nevertheless, the use of camelina by-products as a feed ingredient for poultry has been shown to have potential benefits for both the poultry industry and consumers.

Sensory traits

The effect of the dietary inclusion of camelina by-products on the sensory profile of chicken breast and leg meat are presented in Table 9. The dietary inclusion of either 3% or 6% camelina oil in broiler chickens' diets had no influence on the sensory traits of the cooked meat (Pietras and Orczewska-Dudek 2013). Conversely, the addition of camelina oil (4%) to the broiler diets improved the breast juiciness (Orczewska-Dudek and Pietras 2019). Even the 10% inclusion of camelina cake had no effect on the descriptor used (Orczewska-Dudek and Pietras 2019). When considering the chicken leg meat, Ryhanen et al. (2007) did not observe differences in flavour, juiciness, and tastiness, due to camelina cake-fed diets (5–10% inclusion levels), however the meat obtained from female broilers was significantly more tender compared to that of the control groups.

It is important to note that the sensory traits of poultry meat are influenced by a variety of factors, including genetics, diet, and processing methods. Therefore, further research is needed to fully understand the effects of camelina by-products on the sensory traits of broiler poultry. However, the use of camelina-derived products as a feed ingredient for different poultry species seems to provide potential sensory benefits, in particular on improving the meat tenderness and juiciness, without modifying flavour, taste and odour, considering it somehow a favourable outcome.

CONCLUSION

Inclusion (3–24%) of camelina-derived products (cake or seed) into broiler poultry diets results in increasing the digesta viscosity, thus negatively affecting the digestibility. Inclusion at a higher level (i.e. > 10%) of camelina by-products (seeds or cake), worsened live performance in broiler poultry, whereas oil inclusion displayed satisfactory outcomes. If the diets are supplemented with copper or carbohydrase enzymes, or micronised camelina seeds (with infrared irradiated), this can increase the digestibility of nutrients, thus improving the live performance of broiler poultry. Moreover, carcass traits remained unaffected by the inclusion (2.5–20%) of camelina by-products in different poultry species. The proximate composition of different meat cuts were unchanged. Instead of that, the main classes of fatty acids were strongly affected by the inclusion (2.5–24%) of camelina by-products in poultry species, and an increase (1.32–7.56 times) in ALA was recorded. The dietary inclusion of up to 4% or 10% of camelina oil and cake for broiler poultry did not affect the sensory traits of meat. In general, the magnitude and direction of these effects can depend on factors such as the level of inclusion, the feeding duration, and the basal diet's composition. Further research is needed to fully understand the optimal inclusion level and processing methods for camelina by-products in poultry diets to improve sustainability in poultry production and product quality.

Conflict of interest

The authors declare no conflict of interest.

Table 9. Effect of the dietary inclusion of camelina by-products on sensory profile of chicken breast and leg meat

Species	Matrix	Cut type	Feeding (days)	Inclusion (%)	Anchors†	Flavour	Juiciness	Tenderness	Tastiness	Odour	References
Chicken	control			0		4.50 ± 0.17	4.35 ± 0.37	4.47 ± 0.36	4.33 ± 0.32	4.67	1–3
	oil	breast	49	3, 6	1 to 5	4.70	4.51	4.60	–	4.64	1
			21	4		4.35	4.62*	4.35	4.20		2
	cake	breast	21	10	1 to 5	4.05	4.25	4.26	3.88	–	2
		leg	37	5, 10	1 to 7		4.89	4.99*	4.79	–	3

†Anchors: 1-dislike to 5- or 7-highly appreciated; [1]Pietras and Orczewska-Dudek 2013; [2]Orczewska-Dudek and Pietras 2019; [3]Ryhanen et al. 2007

*$P < 0.05$; **$P < 0.01$ vs control within study

Data are presented as mean value of species-specific control diet ± standard deviation

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