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RAPESEED MEAL AS A FEED COMPONENT IN MONOGASTRIC ANIMAL NUTRITION – A REVIEW

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Abstract

Rapeseed is an important oil crop worldwide, with an annual production of more than 70 million tons. Rapeseed meal (RSM) is a by-product of rapeseed oil production and is second after soybean meal (SBM) in the world production of protein meal. Rapeseed meal derived from black-seeded winter oilseed rape (*Brassica napus* L.) usually contains between 35 and 40% of crude protein (CP), which is considered to be one of the more valuable plant proteins. It has a good balance of essential amino acids and a very high protein efficiency ratio (PER=3.29). However, full utilisation of this protein is difficult due to presence of the non-protein components of the seed which are associated with it. These are called antinutritional factors and they limit the utilisation of RSM in monogastric animal nutrition. The main antinutritional factors in RSM are dietary fibre, glucosinolates, phytic acid, and phenolic compounds (sinapine, tannins). For many years, research has been conducted in many centres around the world to improve the nutritional value of RSM, which will consequently increase its use in feeding monogastric animals. The attempts that have been undertaken include breeding strategy, optimisation, modernisation and better control of the oil extraction process, as well as technological treatments of seeds and meal. This review provides information on how RSM has evolved in recent years, as well as on its nutritive value, particularly protein, fibre and glucosinolate content. Techniques which have been used to improve the nutritional value of rapeseed products are also discussed. However, the used methods do not allow for full replacement soybean meal by RSM in monogastric animal nutrition.

Key words: feed, rapeseed meal, antinutritional factors, protein

The constantly growing world population, improved nutrition in society, and the development of animal production with the use of industrial feed has increased the demand for high-protein meals (Łopaciuk et al., 2019). Additionally, in Europe the use of vegetable high-protein components for feed production is increasing due to the ban on the use of meat and bone meal in livestock nutrition introduced in 2001. The cost of animal production is mainly dependent on the feed price. In any system of poultry or pork production, feed accounts for almost 70% of the total production cost per animal (Khattak et al., 2006; Kim et al., 2015). An increase in the price of soybean meal (SBM) due to high demand has caused an increase in feed cost. Therefore, other cheap protein sources which can replace SBM are being tested (Manyeula et al., 2019; Hao et al., 2020). Rapeseed meal (RSM) and canola meal are a good substitute for SBM in reducing feed cost (Liu et al., 2018). The world harvest of rapeseed in the 2019/2020 season was almost 61 million tons. Globally, processing of rapeseed seeds generates 35.5 million tons of RSM annually (Łopaciuk et al., 2019). In the European Union, Poland is the third largest producer of rapeseed, after France and Germany (Rosiak, 2020). RSM is the second most widely produced protein ingredient for world protein meal production. However, its use in monogastric animal nutrition is still limited due to presence of antinutritional factors (Zhu et al., 2018; Manyeula et al., 2019; Hao et al., 2020). The chemical composition of RSM determines the degree to which it is used in the feeding of various animal species. Utilisation of this by-product as a source of feed protein is also dependent on the sensitivity of various animal groups to antinutritional substances, where younger animals are more vulnerable to the adverse effects of such compounds. Therefore, based on feeding experiments performed on animals of different ages and with different physiological conditions, safe proportions of rapeseed meal in complete feed have been determined. Limits of RSM in feed for pigs (Table 1) have been established at the National Research Institute of Animal Production (Hanczakowska, 2009) and limits for poultry (Table 2) have been determined based on research carried out at the National Research Institute of Animal Production and the Kielanowski Institute of Animal Physiology and Nutrition of the Polish Academy of Sciences (Smulikowska, 2002, 2003).

Traditionally, rapeseed varieties contain from 22 to 60% of erucic acid in their oil and the meal contains about 110–150 µmol/g of aliphatic glucosinolates (Amarowicz et al., 2000; Feng and Zuo, 2015; Kaczmarek et al., 2016; Mejicanos et al., 2016; Beszterda and Nogala-Kałucka, 2019). Over the years, the level of erucic acid

and glucosinolates in the seeds of rapeseed has been reduced significantly. Nowadays, deoiled rapeseed products contain less than 2% of erucic acid and below 30 µmol/g of glucosinolates. Such varieties are called "double-low" or "double-zero" rapeseed in Europe, and "canola" in Australia and North America (Amarowicz et al., 2000; Kasprzak et al., 2016; Stein et al., 2016; Radfar et al., 2017; Beszterda and Nogala-Kałucka, 2019). Despite this spectacular breeding success, there are additional limitations in the practical use of this raw material related to other antinutritional factors, notably dietary fibre (DF), but also phytic acid and phenolic compounds (sinapine, tannins) (Mullan et al., 2000; Jia et al., 2012; Parr et al., 2015; Radfar et al., 2017; Rad-Spice et al., 2018). For years, many attempts have been undertaken to improve the nutritional value of RSM for monogastric animals. These include optimisation and better control of the oil extraction process, selection of low-fibre characteristics (yellow-seeded genotypes), and biological methods such as use of exogenous enzymes and microbial fermentation (Khajali and Slominski, 2012; Beszterda and Nogala-Kałucka, 2019; Hao et al., 2020; Tie et al., 2020).

Table 1. Limits of rapeseed meal in feed and diets for pigs (Hanczakowska, 2009)

Pig age and physiological group	Share of RSM in the mixture (%)
Piglets	3–5
Weaners	6–8
Fatteners 30–60 kg	12–15
Fatteners 61–110 kg	15–20
Post-weaning and early gestation sows	10–15
Late gestation and lactating sows	5

Table 2. Limits of rapeseed meal in feed for poultry (Koreleski and Świątkiewicz, 2009)

Group	Share of RSM in the mixture (%)
Laying hens (brown eggs)	3–5
Laying hens (white eggs)	8–10
Fattening chickens starter feed	5–6
Fattening chickens grower and starter feed	10–12

The aim of this paper is to provide an overview of how RSM has evolved in recent years, and to provide current information about its nutritive value, particularly protein, fibre and glucosinolate content. Techniques which have been used to improve the nutritional value of rapeseed products are also discussed.

Chemical composition of RSM

Nutrients

Protein and amino acids

Rapeseed meal is a good source of protein for animals, but several non-protein chemical components of the seed are associated with protein and alter its nutritional value as well as functional properties, making it difficult to fully utilise (Wanasundara et al., 2016). According to Ayton (2014), protein content in rapeseed is genetically determined and there is an inverse relationship between the oil content and protein content. This relationship is inversely proportional: breeding for higher oil content tends to lower protein content. The amount of this valuable ingredient also depends on the growing conditions. The concentration of crude protein (CP) in meal derived from black-seeded *Brassica napus* is usually between 35 and 40%, whereas the meal obtained from yellow-seeded *Brassica napus* has been shown to be a significantly higher source of this component (Slominski et al., 1999; Khajali and Slominski, 2012; Slominski et al., 2012; Theodoridou and Yu, 2013; Mejicanos et al., 2016; Radfar et al., 2017; Kozlowski et al., 2018). Concentration of CP in meals derived from newly developed yellow lines of rapeseed is nearly 50%. Recently, new varieties of black-seeded rapeseed with increased amounts of CP and meal obtained by the crushing of these seeds with a high content of protein at the level of 45–50% have been introduced to the market (Aider and Barbana, 2011; Liu et al., 2016; Stein et al., 2016). Rapeseed protein is one of the more valuable plant proteins because of its good balance of essential amino acids (Table 3) and very high protein efficiency ratio (PER=3.29) (Khattab and Arntfield, 2009; Radfar et al., 2017; Hao et al., 2020). RSM, like many plant-based protein sources is limited in lysine but noted for having greater levels of sulfur amino acids, cysteine, and methionine, which are in deficit in legume seeds and cereal grains, the main components of feed (Khajali and Slominski, 2012; Liu et al., 2016; Stein et al., 2016; Wanasundara et al., 2016; Liu et al., 2018). Rapeseed meal contains nearly 2% of methionine as a percent of total protein, whereas soybean meal has 1.5%. Compared to SBM, RSM has approximately 10% less available lysine (Mejicanos et al., 2016). Therefore, RSM can be used to balance amino acid in feeds for livestock and poultry. It has been reported that meals derived from rapeseed differ in the colour of the seeds and vary in the amino acid composition of the protein. Slominski et al. (2012) showed that meal derived from a yellow-seeded *Brassica napus* canola contained more total amino acids (+2.6 g per 16 g N) than black-seeded *Brassica napus*, resulting from higher levels of arginine, phenylalanine, asparagine, and glutamic acid. In contrast, the lysine and methionine contents of yellow-seeded *Brassica napus* were lower, meaning that on balance the yellow-seeded type had a slightly poorer amino acid (AA) profile, which from the animal nutrition point of view is considered to be an unfavourable feature.

It is well known that the digestibility of protein in RSM is lower than that of soybean meal. Intestinal digestibility of protein in rapeseed meal for growing pigs is around 72–76% with 87–89% for soybean meal (Grela and Czech, 2019). Furthermore, the digestibility of amino acid in RSM is almost 10% less than in SBM (Li et

al., 2002; Liu et al., 2014, Berrocoso et al., 2015). For example, the lysine standardised ileal digestibility (SID) is greater for SBM (89% to 90%) than for RSM (78%) (Messad et al., 2016). Liu et al. (2018) found that the apparent total tract digestibility and ileal digestibility values in the SBM diet were much higher than those in the RSM diet for growing and finishing pigs. The reduced protein and amino acid digestibility in RSM are to some degree related to genetic and environmental factors, but the main impact is due to processing conditions in the oil factory (Pastuszewska et al., 2003; Khajali and Slominski, 2012; Maison and Stein, 2014; Kasprzak et al., 2016; Mosenthin et al., 2016; Salazar-Villanea et al., 2016). Rapeseed meal processing usually includes cleaning, flaking, cooking, pressing, solvent extraction and desolventising/toasting. All these steps involving wide ranges of temperature, moisture and time and may result in physical and chemical changes of proteins that can influence the final product's digestibility. For example, in the cooker, the temperature ranges from 85 to 95°C, the moisture from 4.5 to 6.0%, and cooking takes 30–40 min. The toasting process time ranges from 35 to 50 min at 95–115°C (Adewole et al., 2016). Excessive heating of RSM during industrial toasting may result in reduced protein solubility and concentrations of AA, notably lysine (Pastuszewska et al., 2003; Adewole et al., 2016; Mosenthin et al., 2016). Undue heat treatment may affect the formation of Maillard reaction products between amino acids and reducing sugars, which are complexes resistant to enzymatic digestion. Moreover, chemical changes may be the result of covalent crosslinking between amino acids (Salazar-Villanea et al., 2016). However, as Salazar-Villanea et al. (2016) showed, these chemical changes of protein do not completely explain the lower digestibility of all amino acids. It is suspected that during rapeseed treatment and oil extraction, changes may appear in the structure of proteins (e.g., secondary and tertiary) that have an impact on the digestion process (Pastuszewska et al., 2003; Salazar-Villanea et al., 2016). Furthermore, during the storage of RSM, modifications of the protein digestibility and availability of amino acids can also occur. Research conducted by Bojanowska (2017) reported a statistically significant decrease in the content of most non-essential amino acids and methionine. Another factor affecting protein digestibility is its interaction with other compounds present in RSM, for example dietary fibre, phytic acid, and tannins.

Rapeseed in comparison to other oilseeds contains two predominant fractions of seed storage proteins (SSP) with different properties: the 2S albumin (napin) and the 12S globulin (cruciferin) (Pudel et al., 2015; Campbell et al., 2016). It also contains slight amounts of proteins, such as thionins, trypsin inhibitors and a lipid transfer protein (Bérot et al., 2005). Cruciferin, which represents 25–65% of the total protein in mature seeds, is a high molecular weight (300 kDa) neutral complex, composed of several polypeptide chains. In contrast, napin, which is present in a lower amount, about 20%, is a low molecular weight (12–17 kDa) basic protein composed of two disulfide-linked polypeptide chains (Wanasundara et al., 2016). Napin contains greater levels of sulfur and aromatic residues (essential amino acids) than cruciferins. According to Pudel et al. (2015), napin is comparable or even better than egg albumin.

Table 3. Amino acid composition of rapeseed (RSM) and soybean meal (SBM) protein (g/16 gN) (Liu et al., 2016)

Amino acid	RSM	SBM
Cystine	2.2	1.2
Aspartic acid	6.3	10.5
Methionine	1.8	1.3
Threonine	3.8	3.6
Serine	3.4	4.0
Glutamic acid	14.0	17.2
Proline	5.8	4.7
Glycine	4.7	4.1
Alanine	4.1	4.1
Valine	4.6	4.5
Isoleucine	3.6	4.2
Leucine	6.6	7.4
Tyrosine	2.6	3.6
Phenylalanine	3.8	4.8
Histidine	2.5	2.5
Lysine	5.2	5.8
Arginine	5.7	7.0

Minerals and vitamins

Rapeseed meal is a good source of minerals and vitamins (Table 4), but with different proportions in comparison to SBM. The calcium, sulfur, magnesium, and phosphorus (P) contents are greater than in soybean meal, but up to 65% of the phosphorus content is bound to phytate, which means that the digestibility of P in RSM is relatively very low (Mejicanos et al., 2016; Stein et al., 2016). The concentration of selenium is 0.16–0.29 mg/kg and is about 10 times higher than that in SBM, but the amount of copper is lower (Feng and Zuo, 2015). Khajali and Slominski (2012) reported that RSM contains less Na and K compared to SBM. For this reason, a RSM-based diet should have an addition of Na to keep an optimal dietary electrolyte balance in the animal body (Weightman et al., 2014). Other important minerals include iron and manganese, 653–687 mg/kg and 78.1–82.2 mg/kg respectively. RSM is also a rich source of niacin, 160 mg/kg, and choline, 6400–6700 mg/kg, whereas carotene and vitamin D are in deficit (Feng and Zuo, 2015). Compared to SBM, concentrations of biotin, folic acid, thiamin and riboflavin are greater in RSM, but pantothenic acid content is lower (Mejicanos et al., 2016).

Table 4. Minerals and vitamins content of rapeseed meal (RSM) and soybean meal (SBM) (Khajali and Slominski, 2012; Mejicanos et al., 2016)

Components	RSM	SBM
Minerals (%)		
calcium	0.7	0.3
sulfur	0.7	0.4
magnesium	0.6	0.3
phosphorus	1.0	0.7
sodium	0.08	0.1
potassium	1.17	2.00
Vitamins (mg/kg)		
niacin	169.5	29.0
pantothenic acid	9.5	16.0
thiamine	5.2	4.5
riboflavin	3.7	2.9
folic acid	2.3	1.3
biotin	1.0	0.3

Carbohydrates

The carbohydrate components of RSM are composed of simple sugars, sucrose, and starch. Simple sugars and starch are present in small quantities, 0.6% and 2–3% respectively. Developing rapeseed embryos accumulate starch, but its level decreases with the increasing rate of storage lipid and protein synthesis. In the mature seeds, lipids comprise up to 45% (Weightman et al., 2014). The sucrose content of RSM varies up to 6–9% (Slominski et al., 2012; Kozlowski et al., 2018). The remaining carbohydrates are antinutritional factors and are described below.

Energy

Rapeseed meal is characterised as having a lower metabolisable energy (ME) level than that of other protein sources such as soybean meal. This low value is largely attributed to the low oil content and high amount of dietary fibre, wherein the energy value of rapeseed meal depends less on fat content than the content of the fibre (Pastuszewska and Raj, 2003; Chibowska et al., 2000; Khajali and Slominski, 2012; Jeroch et al., 2013; Mejicanos et al., 2016; Stein et al., 2016). Typically, rapeseed contains 45–48% fat in dry matter. However, in recent years, genotypes with a very high oil content in the seeds, 54–60%, have been grown (Hu et al., 2013; Beszterda and Nogala-Kałucka, 2019). The amount of residual oil in the meal depends on the efficiency of the extraction process and according to Jeroch et al. (2013) is in the range from 2.4 to 5.0%. Rogiewicz et al. (2012) reported that level of fat in samples obtained from different crushing plants could be as low as 1.4% and as high as 4.3%. Moreover, different contents of residual oil in the meal may vary according to whether or not the crushing plants add gums from oil refining to the meal (Bell, 1993). As Bell (1993) reported, gums may contain about 50% of canola oil and such oil is expected to raise the ME values of the meal. In contrast, the high fibre content reduces metabolisable energy. According to Jia et al. (2012), the differences in the non-starch polysaccharide components in various meals are responsible for the differences in energy utilisation. Dietary fibre, soluble and insoluble, is largely present in the hull and all of it remains in the meal after oil extraction. Neither fractions of fibre are digested by poultry and pigs. Jeroch at al. (2013) reported that dehulling of the seeds before processing in the processing facilities increases the concentration of ME by about 15%.

Antinutritional factors

Dietary fibre

Rapeseed meal contains a high amount of dietary fibre, about 1.5 times more than SBM (31.7% vs. 21.8%). This is a consequence of the relatively large proportion of hulls to seed size (Khajali and Slominski, 2012). A significant part of the rapeseed dietary fibre is found in the hull and constitutes 16–20% of the seed weight (Kaczmarek et al., 2016). According to Kaczmarek et al. (2016), the seed coat (hull) contains 34–42% of crude fibre. After oil extraction, DF constitutes over 1/3 (25–30%) of the mass of RSM and is the main factor limiting its use in feeding monogastric animals (Kaczmarek et al., 2016; Mejicanos et al., 2016). The main components of rapeseed dietary fibre are lignins with associated polyphenols (5–8%) and non-starch polysaccharides (NSP). Lignins have no nutritional value because they are poorly digested in the digestive tract of non-ruminant animals (Noblet and Le Goff, 2001). In the feed, they are only ballast substances and contribute to reducing the ME value of the RSM. In seeds of rapeseed, they are accumulated almost totally in the hull, therefore the lignin content in black-seeded rapeseed is more than two times higher than that in yellow-seeded forms (8% vs. 3.2%) (Carré et al., 2016).

The main components of the NSP of RSM are pectic polysaccharides. The others include cellulose and hemicelluloses (xylans, arabans and xyloglucans) (Sharifi et al., 2013). Cellulose consists of 4–6% NSP, whereas pectic substances, hemicelluloses and protein and minerals associated with these fractions are referred to as non-cellulose polysaccharides (NCP) which comprise 13–16% of NSP. The NSP of double-improved RSM consists of the following monosaccharides: rhamnose, fucose, arabinose, xylose, mannose, galactose, glucose, as well as galacturonic and glucuronic acids. The most abundant of these is glucose (87%), which is mainly a constituent of cellulose (Slominski and Campbell, 1990). The research conducted by Li et al. (2003) showed that yellow-seeded rapeseed compared to black-seeded rapeseed is characterised by lower cellulose content. The non-cellulosic polysaccharides are matrix wall polysaccharides and they do not form a fibrous structure. They are sticking substances and some of them are storage substances. The NCP of double-improved RSM consists of arabinose (33%), xylose (13%), galactose, (12%) glucose (5%),

mannose (3%), rhamnose (2%), fucose (2%) and uronic acids (30%). Their main components are pectic substances, which is indicated by the high concentration of uronic acids. Pectic polysaccharides are mainly composed of rhamnogalacturonan, which includes molecules of galacturonic acid with associated side chains consisting of arabinose, galactose and xylose residues. These sugars are present in short or long complex side chains containing neutral pectic polymers such as arabans, galactans, or arabinogalactans (Slominski and Campbell, 1990; Sharifi et al., 2013; Pustjens et al., 2013). Rapeseed pectins do not contain the (1–4)-linked β-D-gactopyranosyl units that are usually present in soybean pectins. Furthermore, the NCP of double-improved RSM is characterised by a high content of arabinose and xylose, which indicates the presence of hemicelluloses such as xylans, xyloglucans and arabinoxylans in this fibre fraction (Slominski and Campbell, 1990; Egües et al., 2010). The content of these polysaccharides significantly reduces the feed value of RSM. Moreover, an excess of pentosans in the feedstuff causes diarrhoea and poor feed conversion. In addition, these can form complexes with the protein, reducing its digestibility. Cellulose and lignins are largely found in the insoluble dietary fibre (IDF) fraction, whereas its soluble fraction (SDF) consists of pectins, hemicellulose, mixed β-glucans, gums and mucilage (Wanasundara et al., 2016). Ochodzki et al. (1995) reported IDF at a level of 27.5–33.3% and SDF at a level of 3.1–5.2% for both types of rapeseed, spring and winter.

Table 5. The content of different types of fibre in RSM and SBM (% dm)

Type of fibre	RSM		SBM	
	Feng and Zuo (2007)	Chibowska et al. (2000)	Banaszkiewicz (2011)	Banaszkiewicz (2000)
Crude fibre	11.80	12.00	4.3–7.2	6.75
ADF	16.80	23.10	8.9–11.9	9.50
NDF	20.70	36.50	12.3–18.9	15.51

The feed fibre content is usually expressed as crude fibre, acid dietary fibre (ADF) and neutral dietary fibre (NDF). These three types of fibre are not chemically homogeneous compounds and they do not include soluble components. Crude fibre is a component of plant cell walls, primary ones formed during the cell growth period and secondary ones formed later as a result of apposition. Chemically, this fibre is a residue of hot hydrolysis in diluted sulfuric acid (1.25%) and dilute sodium hydroxide and consists of cellulose (50–80%), lignin (10–50%) and trace amounts of hemicelluloses. The crude fibre content does not represent the total amount of these components in the analysed material. Depending on the analysed component of feed, crude fibre may comprise from 40% to 100% of cellulose, 15% to 20% of hemicellulose, and 5% to 90% of lignin (Mertens, 2003). The content of crude fibre in double-improved RSM is between 11% and 12% (Table 5). ADF is an acid detergent extraction residue and includes the least digestible feed components, total cellulose, and lignin, as well as associated protein components and insoluble minerals (Mertens, 2003). NDF is a residue after extraction with a neutral detergent. The composition of the sediment insoluble in neutral detergent consists of the same components as in ADF and hemicellulose. The contents of each fraction of dietary fibre in the RSM depends on the variety, the cultivation method, and the processing of seeds (Adewole et al., 2016; Mosenthin et al., 2016; Salazar-Villanea et al., 2016; Kasprzak et al., 2017). According to Li et al. (2015) in meal derived from black-seeded rapeseed, the average amount of ADF is 23.8%, in a range of 18.8% to 28.2%, and the average amount of NDF is 36.4%, in a range of 27.9% to 41.0%. In terms of the seed processing technology, it was found that the deoiling and toasting stages, in which a heating process is used, increase the content of these two fibre fractions in the meal (Nia and Ingalls, 1992; Almeida et al., 2014). The intensity of temperature, the pressure of the supplied steam, and the duration of exposure are parameters of the heating process which differ between various plants in the oil industry (Pastuszewska et al., 2003). Adewole et al. (2016) showed significant differences in terms of neutral detergent fibre content between meals produced in eleven canola processing facilities in Canada over four successive years (2011–2014). Almeida et al. (2014) found that autoclaving RSM at 130°C for 45 minutes increased the ADF content from 20.0% to 31.3% and the NDF from 33.4% to 46.9%. There are also studies which report that deoiling and toasting have a greater effect on the content of the NDF fraction than on the ADF (Pastuszewska et al., 2003; Mosenthin et al., 2016; Salazar-Villanea et al., 2016). The increase in the analysed NDF, ADF, and lignin contents in all these studies is probably connected with overheating of the meal (Adewole et al., 2016). Excessive heating may lead to the formation of Maillard reaction products which are indicative of protein damage and are responsible for the decrease in protein and amino acid digestibility and would lead to the increase in the analysed NDF, ADF, and lignin contents (Adewole et al., 2016; Salazar-Villanea et al., 2016). Most likely, the analysed concentrations of ADF and lignin increase because some melanoidins, which are polymers originating from Maillard reactions, may be identified as ADF or lignin (Almeida et al. 2014; Adewole et al., 2016). Furthermore, the differences in the NDF content with increasing heat can be attributed to the proteins which are less soluble, and some heat-denatured protein are identified in the NDF fraction (Nia and Ingalls, 1992). It is protein, among all the nutrients, which undergoes the greatest physicochemical changes, especially in its conformation and solubility, which depend on the intensity of temperature and duration of exposure (Pastuszewska et al., 2003; Ivanova et al., 2016; Mosenthin et al., 2016). Theodoridou and Yu (2013) determined the protein content associated with each of these fibre fractions in yel-

low- and black-seeded meal, and obtained lower values for ADF and higher values for NDF. According to these researchers, the amount of protein associated with ADF in the yellow-seeded meal is 0.3% of total protein (TP), and with NDF 8.7% of TP, while in the black-seeded meal these values are 3.1% and 13.1% of TP respectively. The degree of linkage of protein with each fraction of the fibre varies. About 46–56% of the total amount of protein bound to the fibre is associated with pectin, almost 20% with hemicelluloses, 9–11% with lignin, and from 5 to 8% with cellulose (Ochodzki, 1997).

Glucosinolates

Glucosinolates (GLS) were the main factor limiting the utilisation of RSM for animal nutrition before double-zero varieties were introduced into cultivation. These are a large group of sulfur-containing secondary metabolites, which occur in plants of the family *Brassicaceae*. The GLS comprise a β-D-thioglucose group (Figure 1), a sulphonated oxime moiety and a variable side-chain derived from different amino acid precursors (R) (Tripathi and Mishra, 2007; Wittstock and Halkier, 2002). Due to the wide variety of side chain combinations, so far more than 200 types of different glucosinolates have been identified. These are grouped into three classes: aliphatic, indole, and aromatic (Tripathi and Mishra, 2007; Ishida et al, 2014). Plants containing GLS also have the enzyme myrosinase (or its isoenzymes), which mediates their breakdown into harmful derivatives. GLS hydrolysis products show a strong toxicity against many pathogenic fungi, bacteria, viruses, insects and higher plants. Therefore, the myrosinase/glucosinolates system is a defence mechanism of cruciferous plants against pathogens and pests (Patyra et al., 2016). In their native (glycoside) form, glucosinolates are not toxic to animals, but products of their hydrolysis by myrosinase or non-enzymatically by heat or low pH releases various products which may be harmful for animals (Bell, 1993; Khajali and Slominski 2012; Tripathi and Mishra, 2007). The breakdown products of glucosinolates have a bitter taste, thus reducing the palatability of the feed and feed intake, especially in piglets and pigs in initial stages of fattening (Tripathi and Mishra, 2007; Wittkop et al., 2009; Kaczmarek et al., 2016; Wang et al., 2017; Yun et al., 2018). The products of progoitrin hydrolysis are predominantly responsible for the reduction of the palatability of the feed. Progoitrin is degraded by myrosinase or heat exposure to the extremely bitter compound goitrin (Tripathi and Mishra, 2007). GLS are compounds with relatively high chemical stability (Kaczmarek et al., 2016). In the presence of moisture and following rupture of the seed, the GLS are easily hydrolysed by myrosinase enzyme. The process of glucosinolates degradation also occurs in the digestive tract of monogastric animals (Rakowska, 1997; Dinkova-Kostova and Kostov, 2012). For the degradation and transformation of glucosinolates in the digestive tract of poultry and rats, the main factor responsible is the intestinal flora of these animals. In the case of poultry, enzyme-producing bacteria have a similar effect to myrosinase and are present mainly in the caecum and large intestine. According to Khajali and Slominski (2012), in the case of poultry, glucosinolates can be degraded by the microbial population of the lower gut. In this context, the caeca have been identified as the main source of the GLS hydrolytic activity (Khajali and Slominski, 2012). Michaelsen et al. (1994) carried out a rat study on the absorption and transformation of glucosinolates using rapeseed meal containing active and inactivated myrosinase. These authors showed that a large part of the glucosinolates contained in the feed disappears, i.e. is absorbed in the stomach and small intestine, and then in the caecum and large intestine. After thermal inactivation of myrosinase, the absorption of glucosinolates in the stomach and in the upper part of the small intestine did not change, but it was inhibited in the lower part of the small intestine, in the caecum and large intestine. The authors conclude that myrosinase enzymes, which are glycoproteins, are associated with components of rapeseed fibre. Their release in the digestive tract of monogastric animals occurs with the fermentation of rapeseed fibre by the microflora present in the lower parts of the digestive tract. The released enzymes affect the GLS present in the intestinal contents.

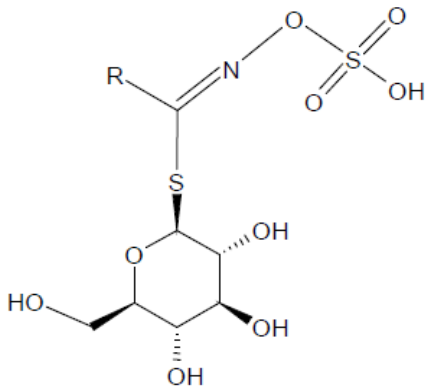


Figure 1. General structure of glucosinolate; R-variable side chain (Wittstock and Halkier, 2002)

Rapeseed myrosinases have the highest thermal stability of *Brassica* spp., and are inactivated by exposure to 70–80°C for 10 min (del Carmen Martinez-Ballesta and Carvajal, 2015), whereas optimum activity for these enzymes is at around 50°C (Weightman et al., 2014). In intact plant tissues, glucosinolates are physically separated from myrosinase. Mechanical damage of plant tissue facilitates contact between the enzyme and the substrate – glucosinolates. The S-glycosidic bond of glucosinolate is hydrolysed, and D-glucose, sulphate and unstable aglycone are released (Figure 2). The aglycones are unstable and, depending on the nature of glucosinolate and pH, the presence of epitiospecific protein and Fe^{+2} ions, they undergo further reactions to form isothiocynates, nitriles, thiocyanates or oxazolidinone (Tripathi and

Mishra, 2007; Ishida et al, 2014). As mentioned before, the breakdown products of GLS are biologically active and known for their diversified biological effects (Tripathi and Mishra, 2007). These substances are absorbed from the digestive tract into the bloodstream of animals and are carried to bodily tissues (Kaczmarek et al., 2016). According to Mejicanos et al. (2016) GLS degradation products impair feed intake due to their bitter taste, and thus growth performance, while also affecting thyroid function by inhibiting thyroid hormone production and impairing liver and kidney function. As mentioned before, progoitrin and sinigrin are responsible for bitterness, with progoitrin producing a more profound bitter taste compared to sinigrin. The reduction of the flavour and palatability of the feed causes its lower consumption, and thus often depresses performance (Tripathi and Mishra, 2007). Products of GLS degradation may disrupt iodine availability to the thyroid, which may result in the increased size of the thyroid gland and reduced plasma concentrations of thyroid hormones (i.e., thyroxine and triiodothyronine) (Tripathi and Mishra, 2007; Stein et al., 2016). The degree of harmful effect of GLS depends on the level and compositions of glucosinolates and their breakdown products, and depends on the species of animal, age and growth state (Tripathi and Mishra, 2007). As mentioned before, myrosinase is inactivated by temperature. Heating rapeseed seeds before grinding at a temperature of about 80°C inactivates this enzyme and reduces the amount of harmful breakdown products. Such a procedure is recommended for seeds which, after deoiling, will be used as a component of feedstuff (Dinkova-Kostova and Kostov, 2012).

Rapeseed contains two types of GLS, aliphatic and indolyl, 85% and 15% respectively (Mejicanos et al., 2016). The predominant aliphatic GLS found in RSM are gluconapin, glucobrassicanapin, progoitrin and napoleiferin, of which progoitrin is the main factor responsible for the antinutritional effect (Mejicanos et al., 2016; Patyra et al., 2016). Traditional varieties of rapeseed contained about 110–150 mg GLS/g of deoiled seeds. In double-improved seeds, the amount of these compounds is 1–2 mg/g, which corresponds to 8–15 µmol/g of deoiled seeds (Rakowska, 1997; Wittkop et al., 2009). According to a recent decision of the European Seed Association (ESA), a variety producing seed with a maximum glucosinolates content of 18 µmol/g has been registered into the Community Catalog of Varieties of Agricultural Plants. Smulikowska et al. (2008) showed the amount of glucosinolates in the black-seed meal to be 10.6 µmol/g, and in the yellow-seed to be 6.2 µmol/g. A current study from processing facilities across Canada reported average amounts of GLS in canola meal at a level 4.6 µmol/g (Adewole et al., 2016). Earlier research has shown that there are already genotypes with a glucosinolates concentration below 2 µmol/g of seeds (Röbbelen and Frauen, 2003). Salazar-Villanea et al. (2016) showed that content of GLS, including the alkene ones, decreases with increased toasting time, with the greatest decrease after 60–80 minutes. It is expected that the requirements for GLS content in rapeseed will become more stringent. As Tripathi and Mishra (2007) reported, a negative correlation between rat growth and the content of glucosinolates in the diet occurred when the content of GLS in the diets exceeded 3.3 or 4.4 µmol/g. According to Bjerg et al. (1989), 0.5 mmol/g is the upper limit of GLS content in feed without negative effects in rats. Therefore, to improve the biological value of RSM and its wider utilization in the nutrition of farm animals, ruminant and monogastric, it is necessary to further reduce the amount of glucosinolates, especially aliphatic ones (Nesi et al., 2008; Wittkop et al., 2009).

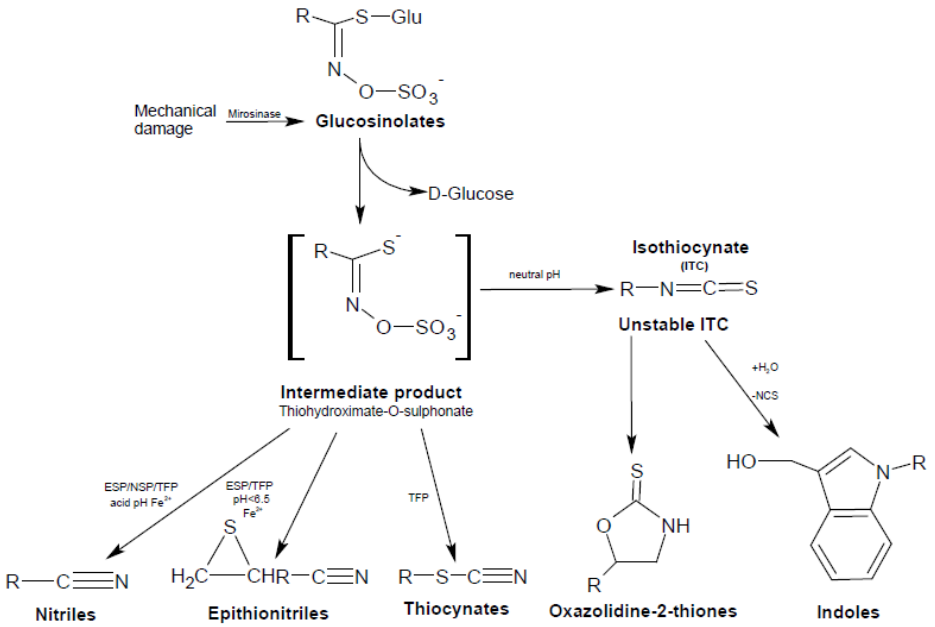


Figure 2. Degradation of glucosinolates catalysed be myrosinase and products of hydrolysis; variable side chain (R) (Wittstock and Halkier, 2002)

Phenolic compounds

Phenolic compounds are secondary metabolites and are derivatives of the pentose phosphate, shikimate, and phenylpropanoid pathways in plants. Rapeseed meal contains more phenolic compounds than any other oilseed meal; for example, compared to soybean meal this is about ten times higher (Xu and Diosady, 2002), 16.9–24.0 mg/g and 0.9–2.6 mg/g respectively (Siger et al., 2004; Mujić et al., 2011). Polyphenols are responsible for the colour, smell and taste of rapeseed products (Naczk et al., 1998). The black colour of the seed coats is due to the presence of polymer leucocyanidins which belong to the group of flavonoids, whereas the yellow colour of the seeds results from disturbances in the metabolism of this group of polyphenols. Over the years, it has been widely believed that yellow-seeded rapeseed has a significantly reduced level of polyphenols compared to the black-seeded variety (Bell, 1993; Rahman et al., 2001; Hernacki, 2007; Khajali and Slominski, 2012). Currently, there are reports in the literature (Jiang et al., 2015), according to which the difference in the content of these components between yellow-seed meal and black-seed meal is insignificant. Lipsa et al. (2007) reported that non-coloured flavonoids have a significant share in total amount of seed flavonoids. These authors showed a very weak correlation between the colour of the seeds and the content of these compounds. According to them, this weak correlation suggests that a significant part of the flavonoids do not affect the dark colour of rapeseed seed but may still have antinutritional effects. Most of the polyphenols present in rapeseed remain in the meal after oil extraction. In small amounts, they have antioxidant activity and protect the feed against autooxidation. However, in greater amounts they form complexes with proteins, amino acids, proteolytic enzymes and other components (e.g. with iron), thus reducing the digestibility and the nutritional value of RSM. Phenolic compounds in RSM bind to the proteins through a variety of mechanisms including hydrogen bonding, covalent bonding, hydrophobic interactions, and ionic bonding. These complex-forming mechanisms make it difficult to separate protein from phenolics (Xu and Diosady, 2002). Furthermore, Mansoori et al. (2015) reported that soluble bioactive components, such as phenolic acids and tannins present in canola meal, have been shown to alter the absorption capacity of chicken intestines for D-xylose and possibly other nutrients which share similar transfer pathways. Therefore, these authors recommend the use of canola meal at levels 5–10% in practical diets for broiler chickens. According to these researchers, at these inclusion levels the soluble bioactive components of canola meal will likely have a negligible effect on the absorption capacity of the intestine for nutrients. The main phenolic compounds found in rapeseed and canola products are phenolic acids, present in free, esterified and insoluble-bound forms and condensed tannins (Naczk et al., 1998).

The total content of phenolic acids in different high-protein rapeseed products ranges from 6.2 to 18.4 mg/g. In rapeseed, phenolic acids are present predominantly in the esterified form. Free acids constitute 6.5–9.0% of the total content of phenolic acids present in RSM with the hull removed and up to 15% in RSM with the hull. The most important compound in this group is sinapic acid, which constitutes 70–85% of free phenolic acids. Other free phenolic acids identified in RSM are *p*-hydroxybenzoic, vanillic, gentisic, protocatechuic, syringic, *p*-coumaric, *cis*- and *trans*-ferulic, coaffeic and chlorogenic acid. Esterified phenolic acids constitute up to 80% of total phenolic acids (Naczk et al., 1998). The most abundant phenolic ester is sinapine, a choline ester of sinapic acid, which accounts for approximately 1% of RSM. Sinapine is thought to contribute to the bitter, sour, and astringent taste of feed, thereby reducing its consumption. This sinapine negative impact on the organoleptic characteristics of feed appears especially in pig nutrition, because poultry have a poorly developed sense of smell and taste (Weightman et al., 2014). Qiao and Classen (2003) reported that in a short-term (from 0 to 18 days) broiler trial, sinapine did not affect feed intake. Sinapine has been implicated with the production of a "fishy" taint in eggs from some brown-egg laying hens. In the organisms of these animals, sinapine is converted by the action of microorganisms in the lower gastrointestinal tract into trimethylamine (TMA), a compound with a characteristic, unpleasant "fishy" smell. Because of a genetic defect, brown-shelled egg-laying hens are unable to convert TMA to the odourless N-oxide oxidase by liver or kidney TMA-oxidase. Undegraded TMA passes into the bloodstream and then into the yolk, giving it a "fishy" smell (Smulikowska and Nguyen, 2003; Khajali and Slominski, 2012). Furthermore, oxazolidine-2-thiones, GLS breakdown products which reduce the activity of TMA oxidase, are responsible for the intensification of the "fishy" smell of eggs (Smulikowska and Nguyen, 2003). In recent years, studies have been initiated which aim to select low sinapine content rapeseed mutants (Wolfram et al., 2010; Harloff et al., 2014).

Rapeseed meal contains approximately 1 mg/g of insoluble phenolic acids, and after dehulling seeds their amount in rapeseed flour is 0.032–0.05 mg/g (Naczk et al., 1998). In this fraction, the predominant acid is sinapic acid (30–59%), followed by *p*-coumaric and *trans*-ferulic acid. Insoluble phenolic acids are bonded in the cell wall to polysaccharides and protein.

Condensed tannins (or proanthocyanidins, PAs) are mostly found in the rapeseed seed coat. Rapeseed meal has been reported to contain about 3% of tannins. In contrast, rapeseed and canola oil-free hulls contain up to 6% condensed tannins (Naczk et al., 2000). Naczk et al. (2000) reported that the insoluble tannins comprise from 70% to 96% of the total PAs. Tannins have a bitter or astringent taste which reduces palatability and hence will negatively affect voluntary feed intake. Tannins can form soluble and insoluble complexes with proteins and proteolytic enzymes in the gastrointestinal tract, thereby reducing protein digestion (Naczk et al., 2000; Khajali

and Slominski, 2012; Beszterda and Nogala-Kałucka, 2019). One mole of tannin is reported to bind 12 moles of protein (Beszterda and Nogala-Kałucka, 2019). It is believed that tannin complexes with protein are created through the formation of hydrogen bridges and hydrophobic interaction, particularly in conditions of low pH, whereas alkaline or neutral pH has an impact on the binding of phenolic acids to proteins (Jędrusek-Golińska et al., 2003). Jędrusek-Golińska et al. (2003) found that the content of polyphenols in rapeseed protein isolate is similar to their amount in meal, approximately 19.4 mg/g and 20.12 mg/g. According to these authors, this is connected with high protein content in the isolate (almost 84%) and the ability of polyphenols to form complexes with such proteins. The separation of proteins from these complexes is complicated, and the removal is incomplete and expensive (Thiyam et al., 2009). Moreover, tannins can form complexes with carbohydrates, especially with starch, and they may reduce the bioavailability of certain minerals (e.g. iron) and vitamins (Barros et al., 2012). The potential future use of RSM as a raw material for the production of protein isolates or concentrates requires additional breeding work to reduce the content of all phenolic compounds, not only sinapine.

Phytic acid

The phosphorous content in RSM is higher than some other plant components. Most of it is presented in the storage form, which is phytates – phytic acids salts (myo-inositol hexakisdihydrogenphosphate-IP_6). Phytic acids levels of 2.0–5.0% have been reported for deoiled meals. Phytates display very limited digestibility in monogastric animals. Non-ruminant animals and fish possess insignificant phytase activity, an enzyme that is needed for the degradation of phytates (Wickramasuriya et al., 2015). As a result, the digestibility of phosphorus in feed containing rapeseed meal does not exceed 30% for pigs and 20% for poultry (Jeroch et al., 2013; Adhikari et al., 2015). The exact role of phytic acid in animal nutrition is not completely understood, but is considered to be an antinutritional factor (Mejicanos et al., 2016). Phytic acid has 12 hydrogen atoms and easily forms complexes with metal cations (Ca, Fe, Zn, Mn, Mg). Complexes of phytic acid with cations are insoluble and poorly hydrolysed in the digestive tract (Anwar et al., 2015). Phytic acid also binds protein and starch. The binding of phytic acid to protein depends on pH; at a pH below the isoelectric point, phytic acid forms insoluble complexes with positively charged proteins. At the isoelectric point, the charges on the protein are reduced and the complexes become soluble. At a pH above the isoelectric point, when the phytic acid and protein are negatively charged, the complexation is carried out by cations such as Ca^{2+} or Mg^{2+}. Phytic acid can form complexes both with food proteins and with proteins of digestive enzymes (amylases, proteinases, trypsin). The protein associated with phytin has a changed structure, which makes it less soluble and less digestible. Phytic acid can also bind starch, directly by forming phosphorus bonds or indirectly through a compound with a protein (Rotkiewicz et al., 1998). The unfavourable effect of phytic acid in feed with RSM can be reduced by exogenous phytase supplementation. Commercial phytases are produced by microorganisms such as moulds, bacteria and yeasts (Khajali and Slominski, 2012). The addition of microbial phytase to feed containing rapeseed meal increases the digestibility of phosphorus in pigs up to 65% and in poultry 50–55% (Jeroch et al., 2013). Increased availability of phosphorus in the gastrointestinal tract translates into less excretion in the faeces, and consequently reduces emissions into the environment (Czerwiński et al., 2012; Jeroch et al., 2013). An additional benefit of the use of phytase in feed is the improvement of animal production parameters (feed consumption, weight gain, feed conversion) by increasing the digestibility of total protein and crude fat (Czerwiński et al., 2012; Walk et al., 2014).

Improving the nutritional value of rapeseed products

According to Pastuszewska and Raj (2003), the value of rapeseed meal as a feed is significantly influenced by the composition of the seeds and the processing technology in various plants of the oil industry. Therefore, the improvement of the nutritional value of rapeseed products can be achieved by breeding and by using appropriate technological treatments: mechanical (dehulling, fractionation, grinding), thermal (heating, steaming and toasting) and biological (enzymatic additives, fermentation).

Breeding strategy to improve the quality of rapeseed seeds

The high content of dietary fibre is considered as the major factor in poor utilization of protein and amino acids from rapeseed meals by simple-stomached animals as compared to soybean meal. Therefore, for over 30 years, around the world intensive work has been carried out to develop yellow-seed varieties, triple-improved (“000”), with a reduced content of erucic acid, glucosinolates and dietary fibre (Meng et al., 1998; Rahman et al., 2001; Relf-Eckstein et al., 2003; Potapov and Osipova, 2004; Hernacki, 2007; Rakow et al., 2007; Rahman and McVetty, 2011; Kozłowski and Jeroch, 2014; Beszterda and Nogala-Kałucka, 2019). Seed colour in rapeseed is associated with coat thickness together with the level of dietary fibre in the meal, thus developing yellow-seeded genotypes with reduced seed-coat thickness was believed to be one of the main goals of the qualitative breeding programme of rapeseed. The greatest amount of fibre is found in the palisade layer, which in yellow seeds is reduced from half to two-thirds, mostly through a lower amount of lignins with associated polyphenols (Rahman et al., 2001; Slominski et al., 2012). The cotyledons of the embryo become visible through the thin, transparent seed coat, which gives the effect of yellow seeds (Hernacki, 2007). The effect of reducing the seed coat thick-

ness, besides a lower content of antinutritional factors, was to increase the amount of nutrients such as protein, fat and sucrose. In more recent years, the value of meal obtained from yellow-seeded genotypes has been widely evaluated (Slominski et al., 1999; Smulikowska et al., 2008; Jia et al., 2012; Slominski et al., 2012; Theodoridou and Yu, 2013; Kozlowski et al., 2018; Rad-Spice et al., 2018). Slominski et al. (2012) examined the chemical and nutritive composition of meals derived from black- and yellow-seeded *Brassica napus* canola (Table 6). Yellow-seeded meal in comparison to black-seeded meal contained more protein (43.8% vs. 49.8%), more glucose and fructose, more sucrose, and less dietary fibre (30.1% vs. 24.1%) and oligosaccharides. According to these authors, the lower fibre content in yellow-seeded meals is connected with a lower content of lignin with associated polyphenols, and some reduction in protein and minerals associated with the fibre fraction. Moreover, the reduction in fibre content is a consequence of the larger seed size, and lower contribution of the hull fraction to the total seed mass (Khajali and Slominski, 2012). Myszka et al. (2011) also evaluated the chemical composition of rapeseed meals obtained from yellow-seeded and black-seeded genotypes. These authors found that meals obtained from seeds of the winter yellow-seeded rapeseed lines were characterised by a significantly reduced (by 27%) content of dietary fibre in comparison with meals obtained from black-seeded rapeseed, and this difference was due to the lower content (more than 4 times) of lignin with associated polyphenols. The content of NSP, which are the main fibre component in rapeseed, was the same in both types of meals and was about 18%. Slominski et al. (2012) reported that in comparison with its black-seeded counterpart, yellow-seeded canola meal contained less glucosinolates. However, in this case the data in the literature are inconclusive. Similar results were obtained by Smulikowska et al. (2008), but Kozlowski et al. (2018) established that yellow-seeded canola meal contained more glucosinolates than its black-seeded counterpart. Likewise, the results of experiments carried out on monogastric animals were not clear. In many cases, there was no improvement observed in growth performance parameters in animals receiving a diet with meal or cake obtained from yellow-seeded rapeseed in comparison to groups fed a diet based on comparable products made from black-seeded rapeseed (Smulikowska et al., 1998, 2008; Jia et al., 2012; Gołębiewska, 2018; Kozlowski et al., 2018; Rad-Spice et al., 2018) (Table 7). Gołębiewska (2018) conducted research whose aim was to determine the nutritional value of new yellow-seeded forms of winter rapeseed in comparison to black-seeded meal and soybean meal. The scope of research included detailed chemical analysis of nutrients and antinutritional components, *in vitro* tests of non-digestible protein-polysaccharide complexes, as well as biological experiments, balance and growth, on rats and broiler chickens. Meals obtained from yellow-seeded forms of winter oilseed rape were characterised by higher protein (46.3% and 41.2% respectively) and mineral contents (8.9% and 8.2% respectively) and lower dietary fibre (28.3% and 37.2% respectively) in comparison to black-seeded meals. Analysis of fibre components showed that the difference between meals obtained from yellow and black seeds was related only to the differences in lignin content (4.2% and 12.6% respectively), whereas the content of non-starch polysaccharides, the main component of rapeseed fibre, was at the same level (17%) in both types of meal. Moreover, the content of arabinose, galactose and glucose, monosaccharides which are components of arabinogalactans, which most often form complexes with proteins in rapeseed, was the same in yellow- and black-seeded meals. The author's *in vitro* and *in vivo* studies on rats and broiler chickens showed that the two types of meal did not differ significantly in terms of protein digestibility, but that this was still significantly lower compared to soybean meal protein digestibility.

Table 6. Chemical composition of black- (BCM) and yellow-seeded (YCM) canola meal (% dm) (Slominski et al., 2012)

Components	YCM	BCM
Crude protein	49.8	43.8
Carbohydrates		
simple sugars	0.2	0.3
sucrose	10.2	8.8
oligosaccharides[1]	2.5	3.1
Dietary fibre	24.1	30.1
nonstarch polysaccharides	18.7	20.2
lignin and polyphenols	3.7	7.1
glycoprotein	1.5	2.1
minerals	0.3	0.7
Ash	7.0	7.3
Glucosinolates	17.1	27.1

[1]Includes raffinose and stachyose.

The reduction of the coat thickness in yellow-seeded rapeseed also has undesirable effects such as reduced crush resistance, which is a problem during storage, less resistance to fungal pathogens and agrochemicals, and accelerated sprouting. Furthermore, in comparison with its black-seeded counterpart, the yields of yellow-seeded rapeseed are 0–30% lower (Hernacki, 2007; Hernacki et al., 2009; Kaczmarek et al., 2016). Due to the growing economic importance of rapeseed all over the world, research on its improvement is continuing. For several years, directions in breeding programmes have been associated with the adaptation of this plant to climate change, competition on the global oilseed market, and the increased use of RSM as feed for monogastric animals. Therefore, the current selection goals include increasing the yield, increasing the amount of oil in seeds, diversifying the composition and proportion of fatty acids in the oil depending on the intended use, as well as increasing the feed value of the meal (Nesi et al., 2008; Bartkowiak-Broda, 2014). There are also works in the field of genetic

engineering aimed at reducing phytate content and increasing phytase activity in rapeseed. Intensive research on the improvement of yellow-seeded lines is continuing, in which efforts are being made to break the coupling of unfavourable features (e.g. reduced mechanical resistance, fertility, reduced resistance to fungal pathogens, accelerated germination), stabilization of the yellow colour of the seeds, and improvement of their chemical composition. The obtained new rapeseed lines are characterised by better features which increase the productivity and quality of the seeds.

Technological treatment of rapeseed seeds

It has been documented that more than 70% of rapeseed fibre is present in the hull (Wickramasuriya et al., 2015; Carré et al., 2016). Consequently, removal of the hull before oil extraction leads to a reduction in the negative effects of the fibre and enhancement of the nutritive value of the meal (Khajali and Slominski, 2012; Kozłowski and Jeroch, 2014). Dehulled RSM in comparison to standard meal is characterised by a significant increase in protein content (40.8% vs. 47.2%) and a considerable decrease in the content of NSP (18.1% vs. 14.7%) and lignin with associated polyphenols (7.7% vs. 4.3%), which are two main components of rapeseed dietary fibre (Khajali and Slominski, 2012). The beneficial effect of removing the hull from the seeds on the improvement of the nutritional value of rapeseed products, related to the increase in the digestibility of amino acids, has been confirmed by nutritional experiments carried out on broiler chickens and pigs (Fang et al., 2009; Jeroch et al., 2013; Kozłowski and Jeroch, 2014). In a study with broilers, Fang et al. (2009) found that birds fed dehulled double-low rapeseed meal (DLRM) diets had a higher growth rate, feed efficiency, and greater digestibility of dry matter, crude protein and neutral detergent fibre, and had a lower feed intake than those fed hulled DLRM diets. Dehulling the seeds most effectively improves the composition and nutritional value of the meal. However, it is technically very difficult and has a negative effect on the quality of the oil, as well as increasing the unit cost of production at the commercial scale. Therefore, it is not likely to be used in practice at present (Pastuszewska and Raj, 2003; Wickramasuriya et al., 2015). Another mechanical treatment is seed fractionation, which consists in their segregation on screens with different mesh sizes. This treatment is intended to obtain a fraction with increased protein content and a reduced fibre content (Brzóska et al., 2010). Work by Mińkowski and Krygier (1998) showed that the size of seeds influences their physicochemical characteristics and, consequently, their technological suitability. Large seeds (2.0–2.5 mm) in comparison with small seeds (1.6–2.0 mm) are characterised by a higher content of fat, protein, metabolisable energy, but also glucosinolates, and a lower content of crude fibre. At the National Research Institute of Animal Production as a result of the segregation of rapeseed meal on screens, the total protein content was increased in meal by 6 percentage units, from 39 to 45%. The obtained meal was used in a feeding experiment on broiler chickens. Reducing the content of soybean meal from 20 to 4%, with a fraction of 18% rapeseed protein meal, lowered the final body weight of the birds by 67 g/head but these differences were not significant (Kamińska et al., 2000). According to Brzóska et al. (2010), a more effective method for the separation of rapeseed meal is pneumatic fractionation. In contrast, Dänicke et al. (1998) reported that the energy value of the seeds, as well as the digestibility of nutrients, depends on the method and degree of their grinding.

Table 7. Comparison of the growth parameters of animals fed with a diet containing meal obtained from black- (BRSM) or yellow-seeded (YRSM) rapeseed (*B. napus*)

Authors	Animal	Type of RSM	Growth parameter		
			feed intake (g)	body weight gain (g)	feed conversion ratio (g feed/g gain)
Smulikowska et al. (1998)	broiler cockerels (8–22 d of age)	BRSM	970	656	1.48
		YRSM	977	660	1.48
Smulikowska et al. (1998)	rats (21 d of age)	BRSM	256.5	77.8	3.33
		YRSM	271.5	87.0	3.16
Jia et al. (2012)	broiler chickens (3–17 d of age)	BRSM	566.4	427.7	1.326
		YRSM	575.5	431.7	1.334
Gołębiewska (2018)	broiler chickens (8–18 d of age)	BRSM	231	99.1	2.372
		YRSM	228	100.5	2.310
Kozlowski et al. (2018)	turkeys (1–8 weeks)	BRSM	120.1*	3.892**	1.728
		YRSM	118.1*	3.906**	1.693
Rad-Spice et al. (2018)	broiler chickens (1–35 d of age)	BRSM	3467	2297	1.51
		YRSM	3378	2187	1.54

*Average daily feed intake (ADFI); **kg.

Commercial seed processing involves many steps, of which thermal treatments have a particular effect on the quality of the final product (Newkirk et al., 2003 a; Pastuszewska and Raj, 2003; Kaczmarek et al., 2016). Thermal treatments reduce the content of some antinutritional compounds. Steam heating of the seeds or cake removes a significant proportion of the glucosinolates (Newkirk et al., 2003 a). According to Eklund et al. (2015) the glucosinolates are efficiently reduced when the residence time in the desolventiser/toaster (DT) increased from 48 to 93 min. In contrast, the SID of most AA in RSM decreased linearly as the residence time in the DT increased from 48 to 93 min. A previous study conducted on broiler chickens by Newkirk et al. (2003 a) showed that the desolventisation/toasting process reduced the coefficient of apparent ileal digestibility (CAID) of most AA, and lysine content, as well as metabolisable energy of canola meal. Pastuszewska and Raj (2003) also reported that toasting has the greatest impact on the available lysine content and protein digestibility. Almeida et al. (2014) reported that heat damage reduces both the concentration and the digestibility of AA in canola meal. According to these authors these results indicate that some of the variations in AA concentration and digestibility among different sources of canola meal fed to pigs are possibly caused by differences in processing, specifically, the desolventisation step, which probably causes Maillard reactions. Additionally, in this experiment the authors created regression equations which may be used to predict the concentration of SID AA in canola meal. Pastuszewska and Raj (2003) suggest that a reduction in toasting temperature from 120ºC to 111ºC increased the content of available lysine from 3.5 to 4.7 g/16N. According to Kaczmarek et al. (2016), toasting of RSM reduces the GLS content and deactivates not only myrosinase but also other beneficial enzymes present in seeds, such as phytase. In contrast, non-toasted canola meal in comparison to conventional toasted canola meal contains higher amounts of digestible amino acids, particularly lysine (Newkirk et al., 2003 b; Pastuszewska et al., 2003). Additionally, non-toasted meal is a light yellow colour, which is more favourably received in some markets. On the other hand, non-toasted meal contains active myrosinase, which hydrolyses the glucosinolates to harmful breakdown products. Therefore, an oil extraction method with modification of current toasting processes should be considered. Such modernization trials of desolventising/toasting have been carried out by some researchers (Kasprzak et al., 2016; Mosenthin et al., 2016). Mosenthin et al. (2016) suggest increasing the residence time under wet toasting conditions or extension of the residence time in combination wet and dry toasting conditions. In a study with growing pigs, Trindade Neto et al. (2012) evaluated meal which was produced using a new, vacuum-assisted cold press of meal desolventisation. As the authors described, in this process, in contrast to conventional desolventiser/toaster, hexane is removed at a lower temperature not exceeding 60°C. Researchers showed that the apparent (AID) and standardised ileal digestibility of protein and amino acids of the tested canola meal differ depending on the processing method used. Osek and Milczarek (2002) evaluated seeds after extrusion. Such seeds, in comparison to seeds that were not extruded, were characterised by a lower content of glucosinolates (by 11%) and tannins (by 5%). Broiler chickens fed the mixture with extruded seeds achieved a final body weight of 3% more compared to the birds fed with natural seeds. In contrast, Kuśnierek et al. (2005) investigated the effect of rapeseed meal extrusion on the digestibility of protein and amino acids in pigs, and glucosinolates level. The authors reported that extrusion of rapeseed meal, especially at 160ºC, caused a decrease in intestinal digestibility and total protein and most of the amino acids compared to non-extruded feed. Extrusion lowered the glucosinolates level from 12.70 μM/g to 9.70 μM/g and 7.70 μM/g, after extrusion at 140 and 160ºC, respectively.

Enzymatic additives

In livestock nutrition, the addition of exogenous enzymes is a commonly used method to improve the utilisation of nutrients from feed. The most frequently used enzyme additives in feed are phytases, proteases, and carbohydrases, which break down selected fibre fractions (Khajali and Slominski, 2012). An essential effect of the application of enzymes on the nutritive value of RSM has been observed with the use of phytase (Mejicanos et al., 2016). For instance, Czerwiński et al. (2012) showed that phytase supplementation of a diet containing rapeseed cake increases phosphorus digestibility and significantly improves the production parameters of chickens. Similar results were reported by Maison et al. (2015) regarding phosphorus digestibility in a study conducted on growing pigs fed different rapeseed products. Most research has evaluated the use of NSP-degrading enzymes to improve carbohydrate digestibility and eliminate the antinutritional effects of dietary fibre. The fact that the use of NSP-degrading enzymes improves digestibility and utilisation of phosphorus by elimination of the phytate chelating effects of NSP was described by Slominski (2011). It is well known that the effect of enzyme preparations consisting of many different enzymes is greater than that of single enzymes, therefore for the hydrolysis of the NSP fraction of rapeseed, multi-carbohydrase enzyme is added. Usually such an enzyme supplement contains cellulase, pectinase, xylanase, glucanase, mannanase, galactanase, amylase, and protease (Thacker, 2001; Józefiak et al., 2010; Jia et al., 2012; Zduńczyk et al., 2013; Radfar et al., 2017; Kozlowski et al., 2018). However, the results of research conducted on various groups of animals in different research centers are not conclusive (Jeroch et al., 2013) (Table 8). Józefiak et al. (2010) found that the use of a combination of multi-carbohydrase and phytase enzymes improved the feed conversion ratio in broiler chickens fed wheat-soybean meal diets containing 6% (starter) and 12% (grower-finisher) of full-fat rapeseed.

Supplementation of the diet with a combination of enzymes also improved the body weight gain of chickens but only up to the 27th day of age. The growth parameters of broilers fed a phytase-supplemented diet did not differ from that of control birds. Fang et al. (2009) reported that the addition of enzyme C (xylanase and cellulase) to dehulled DLRM diets improved the growth rate and feed efficiency of broilers from 4 to 21 days of age, while enzymes A (xylanase and β-glucanase) and B (xylanase) had a positive impact on feed intake and weight gain but did not affect feed efficiency. These authors suggest that reaction of broilers to fibre-degrading enzymes could be improved by hull removal from DRLM. Conversely, Mushtaq et al. (2007) reported that a glucanase and xylanase cocktail had no pronounced effect on the growth performance, nutrient digestibility, or the carcass characteristics of broiler chickens fed with canola meal-based diets. In research conducted by Kozlowski et al. (2018), a multi-carbohydrase enzyme preparation improved feed conversion ratio (FCR) and increased short fatty acid content in the caecal digesta of turkeys. Zduńczyk et al. (2013) evaluated the effect of non-starch polysaccharide-degrading enzymes on the growth performance and gut physiology of growing turkeys. These authors reported that enzyme supplementation increased the growth rate of turkeys and caused ileal viscosity to be reduced, decreased ammonia concentration, increased the glycolytic activities of the intestinal microflora enzymes α-glucosidase, α-galactosidase, and β-galactosidase, and decreased the activity of β-glucuronidase. In a study with broiler chickens, Radfar et al. (2017) found that the inclusion of a multi-carbohydrase enzyme cocktail in conventional, black-seeded *Brassica napus* canola meal-based diet and a canola type yellow-seeded *Brassica juncea* meal-based diet increased metabolisable energy values for both diets and improved the FCR and body weight gain (BWG). However, the most pronounced effect was observed for young birds. Sharifi et al. (2013) conducted experiments on broilers and reported that multienzyme-supplemented diets containing wheat or wheat and canola meal led to significant improvements in growth performance compared with enzyme-unsupplemented diets, which resulted in a decrease of digesta viscosity and increase of villi height and villus height and crypt depth ratio (VH CD) in the small intestine. Jia et al. (2012) carried out a short-term broiler chicken study and showed that multi-carbohydrase supplementation increased the metabolisable energy contents of different canola-meal containing diets, with the most prominent effect observed for *Brassica juncea* canola. In contrast, Thacker (2001) found that enzyme supplementation had no effect on growth performance and apparent total tract digestibility of nutrients in the case of growing pigs fed barley-based diets containing canola meal supplemented with multi-carbohydrase enzymes. Zijlstra et al. (2004) conducted a study on weaned pigs and reported that carbohydrase supplementation to a wheat-canola meal diet increased average daily feed intake (ADFI) and thereby average daily gain (ADG), but not feed efficiency or nutrient digestibility. Fang et al. (2007) fed growing pigs a diet based on corn, soybean meal and Chinese double-low RSM supplemented with NSP-degrading enzymes and found that the enzymes increased the total tract digestibility of dietary energy, neutral detergent fibre and improved ADG, ADFI and FCR. Sanjayan et al. (2014) used weaned pigs to evaluate the effect of multi-carbohydrase enzyme addition to a diet with a high level of canola meals from *Brassica napus* black (BNB) and *Brassica juncea* yellow (BJY) on growth performance and apparent total tract digestibility (ATTD) of crude protein, dry matter (DM), and gross energy (GE). They found that enzyme supplementation had no effect on growth performance but improved the ATTD of DM, CP, and GE in weaned pigs in both the BNB and BJY diets. In a study with fattening pigs, Hanczakowska and Świątkiewicz (2014) found that fibrolytic enzyme supplementation to a diet containing soybean meal, legume seeds and rapeseed press cake had no effect on the performance of fattening pigs, but improved body weight gains of animals receiving field bean. According to Kozłowski and Jeroch (2014), the differences in enzymatic effects reported by researchers are probably attributed to the fact that the tested preparations were developed for NSP contained in cereal grains rather than in rapeseed products.

Table 8. The effects of using feed enzymes in diets containing rapeseed products according to various authors

Authors	Animal	Enzyme	Improvement
1	2	3	4
Czerwiński et al. (2012)	broiler chickens	phytase	P retention, feed intake, body weight gain
Maison et al. (2015)	growing pigs	phytase	apparent total tract digestibility of P, standardized total tract digestibility of P
Thacker et al. (2001)	growing-finishing pigs	protease, cellulase, xylanase, α-galactosidase, amylase	no effects
Zijstra et al. (2004)	weaned pigs	carbohydrase (xylanase and β-glucanase)	average daily feed intake, average daily gain
Fang et al. (2007)	growing pigs	enzyme R (endo-1,4-β-xylanase, endo-1,3 (4)-β-glucanase) enzyme P (endo-1,4-β-xylanase)	total tract digestibility of dietary energy and neutral detergent fibre, average daily gain, average feed intake, feed conversion ratio

Table 8 – contd.

1	2	3	4
Mushtaq et al. (2007)	broiler chickens	endo-1,4-β-xylanase, endo-1,3-β-glucanase	no effects
Fang et al. (2009)	broiler chickens	xylanase cellulase	growth rate and feed efficiency during 4–21d of age
Fang et al. (2009)	broiler chickens	xylanase, β-glucanase	feed intake weight gain
Józefiak et al. (2010)	broiler chickens	phytase, multi-carbohydrase (cellulase, pectinase, mannanase, galactanase, xylanase, glucanase, amylase, protease)	feed conversion ratio body weight gain up to 27d of age
Józefiak et al. (2010)	broiler chickens	phytase	no effects
Jia et al. (2012)	broiler chickens	multi-carbohydrase (pectinase, cellulase, xylanase, glucanase, mannanase, galactanase, invertase, protease, amylase)	metabolisable energy
Sharifi et al. (2013)	broiler	multienzyme (phytase, β-glucanase, α-amylase, cellulase, pectinase, amyloglycosidase, xylanase, protease)	growth performance, decrease of digesta viscosity
Zduńczyk et al. (2013)	turkeys	multi-carbohydrase (pectinase, cellulase, xylanase, glucanase, mannanase, galactanase, protease, amylase)	increased the glycolytic activities of the intestinal microflora enzymes, reduce ileal viscosity, growth rate
Hanczakowska and Świątkiewicz (2014)	fattening pigs	endo-1,4-β-xylanase, endo-1,3 (4)-β-glucanase, pentosanase, hemicellulase, pectinase	body weight gain
Sanjayan et al. (2014)	weaned pigs	multi-carbohydrase (pectinase, cellulase, xylanase, glucanase, mannanase, galactanase, invertase, protease, amylase)	apparent total tract digestibility of dry matter, crude protein and gross energy
Radfar et al. (2017)	broiler chickens	multi-carbohydrase (pectinase, cellulase, xylanase, glucanase, mannanase, galactanase, protease, amylase)	metabolizable energy, feed conversion ratio, body weight gain
Kozlowski et al. (2018)	turkeys	multi-carbohydrase (pectinase, cellulase, xylanase, glucanase, mannanase, galactanase)	feed conversion ratio, increased short fatty acids content in caecal digesta

Fermentation

Recent research has shown that fermented rapeseed meal (FRSM) is a promising alternative protein source and could partially replace soybean meal in animal feeding. According to the literature, microbial fermentation of RSM can be used to increase the amount of protein and to reduce the amount of glucosinolates, crude fibre and phytic acid (Fazhi et al., 2011; Ju et al., 2012; Xu et al., 2012; Aljuobori et al., 2014; Grela, 2016; Mejicanos et al., 2016; Shi et al., 2016; Ashayerizadeh et al., 2017; Czech et al., 2019; Grela et al., 2019; Grela and Czech, 2019; Kiesz, 2019; Chachaj, 2020; Hao et al., 2020; Tie et al., 2020). The fermentation process of RSM improves feed safety through significant elimination of harmful bacteria and reduction of the level of glucosinolates and the products of their breakdown, and increases its palatability and dietary value through the synthesis of short-chain (volatile) fatty acids (Grela and Czech, 2019). Aljuobori et al. (2014) showed that *Lactobacillus salivarius* solid state fermentation (SSF) reduced the total glucosinolate and crude fibre content of RSM by 38% and 16% respectively. Shi et al. (2016) carried out a study whose aim was to improve nutritional quality of RSM using SSF with *Aspergillus niger*. The results of this research also indicated that SSF had significant effects on the chemical composition of RSM. Crude protein increased after fermentation, the amino acid contents of FRSM also increased with the exception of His, which according to the authors may have been attributable to the preferential utilization of His by *A. niger*. Another possible reason for the increase in protein is the loss of dry matter during fermentation. Moreover, the small peptide in FRSM was 2.26 times larger than that in unfermented RSM. Shi et al. (2016) stated that the increasing amounts of small-sized protein may be due to partial digestion of large-sized protein in RSM by protease secreted by *A. niger* during fermentation. However, it is necessary to evaluate the nutritional value and functional characteristics of small-sized peptides before applying these in animal feed production (Tie et al., 2020). The FRSM contained fewer antinutritional compounds, including neutral detergent fibre (NDF), glucosinolates, isothiocyanate, oxazolidithione, and phytic acid than unfermented RSM. The reduction in the content of these

substances in the RSM substrate according to the authors amounted to about 13, 43, 56, 45 and 86%, respectively. According to Shi et al. (2016), the decrease of NDF and glucosinolates in rapeseed meal might be due to many enzymes secreted by *A. niger* during SSF. *A. niger* is able to secrete many extracellular degradation enzymes, especially lignocellulosic hydrolysing enzymes which are hydrolysis components of fibre. Reduction of phytic acid in this study may also be caused by *A. niger,* which has the ability to secrete phytase, which causes the breakdown of phytate during the fermentation of RSM. However, according to Shi et al. (2016), the mechanism of SSF is still not clear and needs more research. Tie et al. (2020) developed a two-stage biological method for the degradation of antinutritional factors and the improvement of the protein quality of RSM. The first stage is *Aspergillus niger* solid state fermentation, and the second stage is enzymatic hydrolysis to further degrade the antinutritional factors and macromolecular proteins in the fermented RSM. According to the authors, this method is more effective than the single-stage fermentation. The two-stage method resulted in a significant reduction in GLS and phytic acid levels in RSM compared with those obtained by the fermentation method alone. The crude protein digestibility increased by this combined approach, probably due to the partial degradation of storage proteins into simpler and more soluble molecules. Tie et al. (2020) reported that crude protein content was also significantly increased after fermentation of rapeseed meal but was not changed after enzymatic hydrolysis. These authors state that crude protein content increased probably due to the activities of *Aspergillus niger,* which produces many hydrolytic enzymes that reduce the levels of residual lipids and carbohydrates via their conversion into cell mass and carbonaceous gas during fermentation. Moreover, the total AA content was also increased, which could be attributed to the synthesis of bacterial proteins from inorganic nitrogen during fermentation. According to the authors of these studies, after the first fermentation stage, the content of six essential AA (Ile, Leu, Lys, Met, Phe, and Thr) was increased, whereas that of Arg, His, and Val was not significantly changed. After enzymatic hydrolysis, the content of Lys, Phe, Ser, Glu, and Ala was significantly reduced, whereas the level of Val was increased by 15.66% compared with that obtained after fermentation. However, more research is needed to investigate the mechanisms of enzymatic hydrolysis following SSF. Pioneering research into the effect of static-state fermentation on volatile composition in RSM was carried out by Hao et al. (2020). The researchers tried to explain the differences in volatiles among RSM before and after fermentation and of FRSM after different fermentation times. To understand the effect of static-state fermentation on RSM aroma, the volatile compounds of rapeseed meal during different stages of fermentation were analysed using an electronic nose system and headspace solid-phase microextraction–gas chromatography–mass spectrometry. As in the previously described studies, fermentation significantly decreased the amount of glucosinolates, total tannins, phytic acid, and crude fibre, whereas it increased the content of crude protein, water-soluble protein and peptides, essential and total amino acids. The most significant differences in content of volatile flavour compounds were observed between the raw RSM and day 5 samples, which indicate the great change in volatile components of RSM during fermentation. Hao et al. (2020) identified fifty-two volatile compounds by GC–MS and then classified them into 11 categories: hydrocarbons, aldehydes, alcohols, esters, phenols, acids, ketones, pyrazines, amines, nitriles, and others. The volatile components of RSM were mainly hydrocarbons and aldehydes. The main volatile compounds from RSM samples fermented for 5 days were a variety of pyrazines, acids, amines, and nitriles. According to the authors, differences in the content of volatile compounds may have been caused by the emergence or disappearance of some volatile compounds and changes in the concentration of similar volatile compounds. Generation of flavour and functional substances may have been caused by the catalytic decomposition of proteins, fats, and carbohydrates in RSM by various enzymes from microorganisms. The results of this study are very useful because they can help to improve the flavour quality of FRSM and its processing technology.

Table 9. The effects of using fermented RSM in diets for monogastric animals according to various authors

Authors	Animal	Improvement
1	2	3
Xu et al. (2012)	broiler chickens	increase the level of IgG, IgM and total P and Ca content, intestinal morphology
Ashayerizadeh et al. (2017)	broiler chickens	weight gain, feed conversion ratio, reduce the colonization of *S. Typhimurium* in gut and internal organs and decrease stress
Ashayerizadeh et al. (2018)	broiler chickens	growth performance, balance of desirable gastrointestinal microflora and lipid profile of blood serum, beneficial effect on meat quality and fatty acid profile, and enhance antioxidant activities of breast and thigh muscles
Chiang et al. (2010)	broiler chickens	weight gain, feed conversion ratio, nutrient digestibility, increased the numbers of lactobacilli in the colon and caeca and enhanced the small intestinal structure of the broilers
Fazhi et al. (2011)	ducks	daily gain, phosphorus and calcium content in serum, increase the level of IgG, IgM

Table 9 – contd.

1	2	3
Czech et al. (2019)	sows, during pregnancy and lactation period	stimulate the immune system of sows, improve quality of colostrum and health of piglets, reduce diarrhoea severity and mortality, growth performance
Grela et al. (2019)	sows	production parameters, mainly in primiparous gilts, stimulate the immune system of sows, improve quality of colostrum and health of piglets, reduce diarrhoea severity and mortality, digestibility of crude protein, fat and crude fibre and positively affect the gut microbiota of sows
Kiesz (2018)	piglets	positive effect on the microbiological composition and histological image of the intestines, digestibility of nutrients and the value of production indicators, stimulate the immune system

Many attempts to partially replace soybean meal with fermented rapeseed meal in the diets of broilers and pigs have been made (Xu et al., 2012; Ashayerizadeh et al., 2017, 2018) (Table 9). Xu et al. (2012) reported that RSM fermented with *Lactobacillus fermentum* and *Bacillus subtilis* is a promising alternative protein source and that it could be safely used to replace up to 10% SBM in broiler diets. According to these authors, FRSM at not more than 10% of the diet did not decrease the performance of chicks, but increased the level of IgG, IgM and total P and Ca content and decreased the UN content in serum. Moreover, the intestinal morphology of broilers fed with 10% FRSM was improved. These birds were characterised by increased villus height of the duodenum and jejunum mucosa, observed during the whole experimental stage. Ashayerizadeh et al. (2017) conducted a study whose aim was to assess the effects of fermented rapeseed meal on *Salmonella enterica* serovar Typhimurium (*S. Typhimurium*) colonization and on growth performance in broiler chicks. According to Ashayerizadeh et al. (2017), birds fed FRSM had significantly higher weight gain and better FCR compared to those fed RSM. Furthermore, FRSM reduces the colonization of *S. Typhimurium* in the gut and internal organs and decreases stress. The authors of this study state that FRSM in addition to a processed protein source can even be considered as a new strategy for controlling Salmonella infection in broiler chicks. Subsequent research by Ashayerizadeh et al. (2018) was aimed at evaluating the effects of replacing SBM with RSM or FRSM in diets on growth performance, gastrointestinal microflora population, blood metabolites, meat quality, and lipid metabolism in broiler chickens. The results showed that replacing SBM with FRSM compared to RSM improves growth performance, the balance of desirable gastrointestinal microflora, and the lipid profile of blood serum, positively affects meat quality and fatty acid profile, and enhances antioxidant activities in the breast and thigh muscles. These results are very useful for producing fast-growing broiler chickens with a beneficial fatty acid composition of meat for the consumers. In 2020, the average consumption of meat in the world was 33.7 kg per capita, of which 14.9 kg was poultry, 10.7 kg pork, 6.4 kg beef, and 1.76 kg lamb and mutton. Poultry consumption is the largest, therefore, it is important that consumers consume the highest quality meat. A previous study conducted by Chiang et al. (2010) showed that weight gain and feed conversion of birds fed FRSM were superior to those of birds fed non-fermented rapeseed meal and did not differ from the soybean control. Furthermore, in comparison with unfermented rapeseed meal, solid-state fermentation improved nutrient digestibility, increased the numbers of lactobacilli in the colon and caeca, and enhanced the small intestinal structure of the broilers. Research carried out by Fazhi et al. (2011) showed that fermented rapeseed meal can completely replace soybean meal in a duck diet and potentially reduce the cost of duck production. Czech et al. (2019) conducted research whose aim was to assess the effectiveness of fermented rapeseed meal in diets for sows, during pregnancy and the lactation period. The results of this experiment show that using FRSM is an effective way to stimulate the immune system, which improves the quality of colostrum and the health of piglets, reducing the severity of diarrhea and mortality. Moreover, the authors reported that a share of FRSM in feed significantly improved growth performance, leading to growth in the number of piglets in the litter and the weight of the litter at 28 days of age, and better utilization of minerals, e.g. phosphorus, calcium, copper and iron from feed mixtures. According to Grela et al., (2019) the addition of a 4% to 9% share of an FRSM component in diets for sows significantly improves production parameters, mainly in primiparous gilts, leading to an increase in litter size and in litter weight at 28 days of age. Similar to the previously described studies, these authors also reported that using FRSM as a feed component stimulates the immune system, which improves the health of piglets, reducing the severity of diarrhea and mortality. Moreover, it improves the digestibility of crude protein, fat and crude fibre and positively affects the gut microbiota of sows (especially gilts during late pregnancy).

A new issue is also raised by plant fermented protein concentrates (FPC). FPC are manufactured as a result of patented production technologies, and the obtained products contain 30–50% of high-value protein. Examples are EP 100 and EP 200 protein concentrates obtained from the fermentation of feeds such as rapeseed meal, soybean meal, wheat and potatoes, after which they are dried and packaged for sale (Grela, 2016). There are few reports of their impact on the growth performance of pigs fed in the

dry system. The research of Kiesz (2018) showed that feeding piglets a mixture with 8% or 6% of dried FRSM had a positive effect on the microbiological composition and histological image of the intestines and improved the digestibility of nutrients and the value of production indicators, and also stimulated the immune system. However, considering the course of processes related to mineral and lipid metabolism as well as the stimulation of erythropoietic and antioxidant processes, the most favourable solution is a combination of dried fermented rapeseed meal with dried fermented soybean meal, 6% and 2% respectively.

Conclusions

The increasing costs of animal diets are important for the wider use of alternative feed ingredients for economically effective animal production. Therefore, in recent years, finding new protein sources has become a major focus in animal production. Rapeseed meal offers a great potential for monogastric animals as an alternative feed ingredient. However, the utilisation of valuable rapeseed protein in poultry and pig feeding is still limited. Therefore, more research is needed to improve its nutritional value. For years, it was expected that the development of yellow-seeded forms would be the next stage of breeding works to improving the nutritional value of RSM. Research on the chemical composition of yellow-seeded rapeseed showed a higher protein and fat content and lower fibre content in these seeds in comparison to traditional black-seed varieties. However, the content of non-starch polysaccharides, the main component of the rapeseed seed's dietary fibre, is at a similar level in both types of meal. Likewise, the content of arabinose, galactose and glucose, monosaccharides which are components of arabinogalactans, which most often form complexes with proteins in rapeseed, is the same in yellow- and black-seed meals. Moreover, the published results of experiments carried out on monogastric animals were not clear. To increase the use of RSM as a raw material for the production of feed, protein isolates or concentrates will require additional breeding work to reduce the content of non-starch polysaccharides, sinapine, and glucosinolates. For many years, there have also been attempts to optimize the addition of enzymes to feed with RSM. Enzymes are very useful tools in works aimed at improving utilization of RSM, but to achieve profit in commercial monogastric animal feeding, the correct blend of multiple enzymes is required. Such a mixture should improve the feed conversion ratio, body weight gain, and nutrient digestibility. Recent research has shown that fermented RSM and dried FRSM is a promising alternative protein source in monogastric animal nutrition. Enzymes secreted by microorganisms might result in the improvement of the nutritional value of RSM. However, more research is needed to investigate the mechanisms of fermentation and its products, as well as to develop technology for obtaining FRSM on an industrial scale, and to implement this new approach on pig and poultry farms. Moreover, the value of rapeseed meal as a feed component is significantly influenced by the seed processing technology. Hence, the industrial oil extraction process should be modified towards optimisation and standardisation of thermal treatment, which has the strongest impact on RSM quality. This would be valuable to the feed industry, as it may create a product that is less variable in amino acid composition and digestibility.

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