Review

Factors that affect the nutritive value of canola meal for poultry

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ABSTRACT This article reviews the factors affecting the nutritive value of canola meal (CM), including glucosinolates, sinapine, phytic acid, tannins, dietary fiber, and electrolyte balance. It also addresses the means of improving the nutritive value of CM throughout seed dehulling, development of low-fiber canola, or application of feed enzymes. Over the years, the glucosinolate content of canola has been declining steadily and is now only about one-twelfth of that of the older high-glucosinolate rapeseed (that is, 10 vs. 120 μmol/g). Therefore, the rations for broilers or laying hens could now contain 20% of CM without producing any adverse effects. Tannins are of lesser importance due to their presence in the hull fraction and thus low water solubility. Sinapine has been implicated with the production of a "fishy" taint in brown-shelled eggs, which results from a genetic defect among the strain of Rhode Island Red laying hens. The White Leghorns have been reported not to be affected. Although lower in protein, CM compares favorably with soybean meal with regard to amino acid content. Because CM contains more methionine and cysteine but less lysine, both meals tend to complement each other when used together in poultry diets. Canola meal is low in arginine (Arg) which could be of importance when introducing CM to broiler diets at high inclusion rates. The Arg content of CM is approximately two-thirds of that of soybean meal. Chickens fail to synthesize Arg and are highly dependent on dietary sources for this amino acid. Supplementation of Arg to CM-based diets has been shown to partly restore the growth performance. Dietary cation-anion difference in CM is also less than optimal due to the high sulfur and low potassium contents. Seed dehulling has not been very successful due to excessive fineness and thus difficulties with percolation of the miscella through the cake. Development of low-fiber, yellow-seeded canola and the use of enzymes have proven to increase the energy utilization and the nutritive value of CM for poultry.

Key words: canola meal, chemical composition, dietary fiber, enzyme, poultry

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INTRODUCTION

The global production of rapeseed, including canola varieties, ranks second among oilseed crops (USDA, 2011). The composition of rapeseed has been remarkably altered by plant breeders who have developed new varieties of rapeseed, known as double-zero rapeseed or canola. The term "canola" presently used in Canada is being adopted in the United Kingdom, Australia, and the United States to describe the rapeseed of *Brassica napus* species yielding oil of less than 2% erucic acid and meal of less than 30 μmol/g of aliphatic glucosinolates.

Association of erucic acid consumption with the myocardial lesions in laboratory animals committed Canada and other countries to shift their rapeseed production to low-erucic acid varieties. In Canada, this change was completed in the late 1970s. The second major quality improvement came in the mid 1970s as canola breeders lowered the content of undesirable glucosinolates (**GLS**) in the seed. A complete changeover to canola varieties was achieved in 1984, where even the high-erucic rapeseed contracted for industrial use was of "canola" characteristics with regard to GLS content.

Although canola meal (**CM**) is commonly used in poultry diets as an economically viable alternative to soybean meal (**SBM**), its use is still restricted to less than full replacement of SBM due to the low available energy content and the presence of antinutrititional factors.

CHEMICAL COMPOSITION OF CANOLA MEAL

The main components of canola meal (prepress solvent extracted) include protein, carbohydrates (that is, simple sugars, sucrose, oligosaccharides, starch), dietary fiber (that is, nonstarch polysaccharides, lignin

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with associated polyphenols, glycoproteins), fat, and ash (Table 1). Although lower in protein, CM compares favorably with SBM with regard to amino acid content. Because CM contains more methionine and cysteine but less lysine, both meals tend to complement each other when used together in rations for livestock and poultry. Also, the fat content is higher than that of SBM due to the presence of gums (that is, phospholipids, glycolipids, triglycerides, and free fatty acids) which are often added back to the meal after oil refining. Canola meal is a good source of available calcium, iron, manganese, selenium, and many of the B vitamins (Newkirk, 2009). Although high in phytate, CM is also one of the richest sources of nonphytate (available) phosphorus (that is, 0.38% of nonphytate P vs. 0.28, 0.23, 0.09, 0.26, 0.07, and 0.13% for SBM, cottonseed meal, wheat, wheat bran, corn, and barley, respectively).

The carbohydrate components of CM account for approximately one-third of the meal and are composed of simple sugars, sucrose, oligosaccharides, starch, and nonstarch polysaccharides (**NSP**; Table 1). The level of low-molecular weight carbohydrates in CM is similar to that of SBM, although SBM contains greater concentration of the oligosaccharides raffinose and stachyose.

As a consequence of the small size and high oil content in the seed (42–45%), the resulting meal contains a relatively high proportion of fiber. The crude fiber (**CF**), acid detergent fiber (**ADF**), neutral detergent fiber (**NDF**), and total dietary fiber values for CM are higher than those of SBM due to a much higher content of lignin with associated polyphenols (tannins). The fiber components of CM have been shown to be inversely related to energy digestibility (Downey and Bell, 1990). As indicated in Table 1, the metabolizable energy content of CM averages 2,000 kcal/kg for poultry and is lower by 230 kcal/kg (10% moisture basis) than that of SBM (NRC, 1994).

Table 1. Chemical and nutritive composition of canola meal and soybean meal (%; 10% moisture basis)[1]

Component	Canola meal	Soybean meal[2]
CP	36.5	45.6
Ether extract	3.6	1.3
Ash	6.8	6.4
Amino acids		
Arginine	2.04	3.23
Lysine	2.00	2.86
Threonine	1.57	1.74
Methionine	0.74	0.65
Cystine	0.85	0.67
Tryptophan	0.48	0.64
Carbohydrates		
Simple sugars[3]	0.6	0.6
Sucrose	6.0	6.2
Oligosaccharides[4]	2.0	5.6
Starch	2.4	2.3
Dietary fiber fractions		
Crude fiber	11.6	5.4
Acid detergent fiber	18.2	7.5
Neutral detergent fiber	26.0	12.0
Total fiber	31.7	21.8
Nonstarch polysaccharides	18.0	17.8
Lignin and polyphenols	10.4	2.6
Glycoproteins	3.3	1.4
Calcium	0.67	0.33
Phosphorus (P)	1.02	0.66
Phytate P	0.64	0.38
Nonphytate P	0.38	0.28
Sinapine	1.0	NA[5]
Glucosinolates[6] (μmol/g)	5.5	NA
Metabolizable energy (kcal/kg)	2,000	2,230

[1]Average values calculated from Hubbell (1989); NRC (1994); Ewing (1997); Leeson and Summers (2005); Selle and Ravindran (2007); Newkirk (2009); Rogiewicz et al. (2012).

[2]The numbers for soybean meal are the means of 5 different complete data sets, including both low- and high-protein soybean meal.

[3]Includes glucose and fructose.

[4]Includes raffinose and stachyose.

[5]NA = not applicable.

[6]Includes gluconapin, glucobrassicanapin, progoitrin, gluconapoleiferin, glucobrassicin, and 4-hydroxyglucobrassicin.

FACTORS AFFECTING THE NUTRITIVE VALUE OF CANOLA MEAL

Glucosinolates

The GLS are a large group of sulfur-containing secondary plant metabolites, which occur in all the economically important cruciferous plants. A wide variety of GLS exists according to modification of the side-chain structure (Figure 1). Up to now, more than 120 different GLS have been identified (Chen and Andreasson, 2001). The major GLS present in CM are gluconapin (3-butenyl), glucobrassicanapin (4-pentenyl), progoitrin (2-hydroxy-3-butenyl), gluconapoleiferin (2-hydroxy-4-pentenyl), glucobrassicin (3-indolylmethyl), and 4-hydroxyglucobrassicin (4-hydroxy-3-indolylmethyl; Bell, 1984; Slominski and Campbell, 1987; Shahidi and Gabon, 2007).

It is generally believed that GLS, per se, are nontoxic. However, they are always accompanied by the enzyme myrosinase (thioglucoside glucohydrolase, EC 3.2.3.1) in the seed. In the presence of moisture and following rupture of the seed, the GLS are hydrolyzed to yield unstable aglucones which then break down to yield a range of products, including isothiocyanates, goitrin, nitriles, and thiocyanates, that interfere with the function of thyroid gland and adversely affect growth performance (Fenwick, 1982; McCurdy, 1990; Tripathi and Mishra, 2007). Although the myrosinase

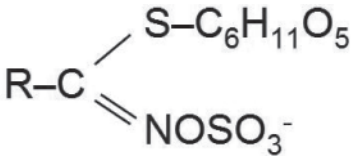

Figure 1. Structures and names of the most abundant glucosinolates of canola meal. R = 3-butenyl- (gluconapin); R = 4-pentenyl- (glucobrassicanapin); R = 2-hydroxy-3-butenyl- (progoitrin); R = 2-hydroxy-4-pentenyl- (gluconapoleiferin); R = 3-indolylmethyl- (glucobrassicin); R = 4-hydroxy-3-indolylmethyl- (4-hydroxyglucobrassicin).

enzyme is effectively inactivated by heat-treatment applied in the crushing operation of canola seed, some thermal decomposition of GLS may occur and result in the formation of similar breakdown products (Campbell and Slominski, 1990). Glucosinolates can also be degraded by microbial population of the lower gut with the greater amount of disappearance observed for aliphatic than for aromatic (that is, indole) glucosinolates (Slominski et al., 1987, 1988; Campbell and Slominski, 1989). In this context, the ceca have been identified as the major source of the GLS hydrolytic activity.

Early adverse effects observed when high-GLS rapeseed meals were fed to monogastric animals were due to the pungency of isothiocyanates, antithyroid activity, and bitterness of goitrin or a combination of their deleterious properties. Detailed studies on the nitrile 1-cyano-3-hydroxybutene, the major GLS breakdown product of rapeseed meal, have not confirmed a common perception with regard to its toxic properties (Papas et al., 1979; Slominski and Rakowska, 1985).

The adverse effects of GLS have been reported to have more severe effects in laying hens than in broilers (Fenwick, 1982). In earlier research, high levels of GLS have been implicated with the reduced egg production and mortality due to hemorrhagic liver syndrome. In a study by Ibrahim and Hill (1980), a diet containing high-glucosinolate rapeseed meal (200 g/kg) and fed to laying hens depressed egg production when compared with a diet containing SBM. The mortality due to hemorrhagic liver syndrome was attributed to the high glucosinolate content. In the same study, a diet containing low-glucosinolates rapeseed meal (200 g/kg) derived from the low-glucosinolate Canadian variety Tower did not depress the egg production. In another study, feeding rapeseed meal high in glucosinolates decreased egg production, caused liver enlargement, and reduced plasma uric acid concentration. These effects were exacerbated by the addition of myrosinase and thus the production of GLS toxic end products (Martland et al., 1984). In another study (Smith and Campbell, 1976) the detrimental effects of high-glucosinolate RSM in laying hens were attributed to the glucosinolate breakdown products because nitrile derived from progoitrin, the major glucosinolate of rapeseed, was detected in the contents of the digestive tract. In a review of literature, Mawson et al. (1994) discussed different recommendations for the inclusion rate of low-glucosinolate rapeseed meal (canola) in the diets for laying hens. Some authors recommend limiting the inclusion rate to 10%, whereas others did not find any adverse effect on egg production at the inclusion rate of 20%.

In broiler chickens, feeding a high level of dietary GLS resulted in reduced feed intake, growth rate, and increased mortality (McNeill et al., 2004). Leeson et al. (1987) found a dietary GLS tolerance of up to 11.6 μmol/g in broilers. In another study, however, it has been reported that the GLS content above 8.0 μmol/g of diet would result in a severe growth depression (Tripathi and Mishra, 2007). As reported by Mawson et al. (1994), the growth depression attributable to dietary GLS would be minimal at the GLS level of 4 μmol/g of diet. However, when the levels of GLS increased to 6 to 10 μmol/g, some reduction in growth was observed, with the level of GLS above 10 μmol/g resulting in a severe growth depression.

Over the years, the GLS content of double-zero rapeseed or canola has been declining steadily and is now only about one-twelfth that of the older high-GLS rapeseed. Current annual reports by the Canadian International Grains Institute (Newkirk, 2009) indicate the GLS content of canola seed, including indole GLS, to be about 10 μmol/g (as-fed, fat-free basis). An earlier report from Australia revealed an average of 11 μmol of GLS per gram of meal (Mailer and Cornish, 1987) whereas that from South Africa indicated 18 μmol/g (fat-free basis; Brand et al., 2007). Such levels would further be reduced due to GLS decomposition during seed processing, including the most common prepress solvent extraction process. Based on the recent survey involving 11 crushing plants across Canada, the level of GLS averaged 3.9 μmol/g (10% moisture basis; Rogiewicz et al., 2012). A recent report on the GLS content of meals derived from 9 crushing plants in France showed an average value of 10 μmol/g (Labalette et al., 2011). The level of 4.3 μmol/g was recently reported for the commercial meal used in Poland (Mikulski et al., 2012).

Considering a conservative 4 μmol per gram of diet as the maximum level of GLS inclusion rate, it would appear that rations for broiler chickens could contain significantly more CM than the currently recommended 20% without producing any adverse effects due to GLS. However, a "no-effect" of GLS of approximately 1.5 μmol per gram has been reported for laying hens because of their association with mortality due to hemorrhagic liver syndrome (Campbell and Slominski, 1991). With the current levels of GLS, a content of 1.5 μmol/g would approximate the level that would be present in a laying hen diet containing 15 to 20% of CM.

Tannins

Tannins are complex polyphenolic compounds having molecular weights in the range of 500 to 3,000 Da. They can be subdivided into hydrolysable and condensed fractions (Yapar and Clandinin, 1972). The presence of condensed tannins in rapeseed hulls was first reported by Bate-Smith and Ribereau-Gayon (1959). This finding was verified by Durkee (1971), who identified cyanidin, pelargonidin, and *n*-butyl derivative of cyanidin in the hydrolytic products of rapeseed hulls. Later, Leung et al. (1979) reported that condensed tannins of rapeseed hulls contained leucocyanidin as their basic units. Structure and chemistry of the condensed tannins have been described by Schofield et al. (2001). The condensed tannins are mostly found in seed coat with the brown hulls containing more than the yellow hulls (Durkee, 1971; Theander et al., 1977). Naczk et

al. (2000) reported that the total amount of tannins in rapeseed/canola hulls ranges from 1.9 to 6.2 g per 100 g of oil-free hulls. Insoluble tannins predominate in canola/rapeseed hulls and comprise from 70 to 96% of the total tannins present. In addition to giving the meal a dark unattractive color, tannins may form complexes with protein and proteolytic enzymes in the gastrointestinal tract, thereby affecting protein digestion. Tannins have also been reported to bind other enzymes, but Mitaru et al. (1982, 1983) and Yapar and Clandinin (1972) failed to demonstrate α-amylase binding by rapeseed tannins. However, removal of tannins from the meal significantly increased the metabolizable energy of the meal, probably due to increased activities of endogenous enzymes. Conversely, addition of tannic acid at 1.5% to broiler diets resulted in a severe growth depression (Leslie et al., 1976). Research has shown that endogenous amino acid losses were significantly increased following dietary tannic acid addition. The amino acids most affected were methionine, histidine, and lysine while the least affected included threonine, cysteine, and valine when 10 g per kilogram of diet of tannic acid was administered (Mansoori and Acamovic, 2007). It would appear from this study that water-soluble tannins (tannic acid) could, in part, be responsible for poor growth performance of broiler chickens. However, in light of the fact that canola tannins are for the most part water-insoluble and are located within the cell walls of the hull fraction, it is reasonable to assume that their antinutritive effect would be minimal.

Phytic Acid

Phytic acid [myo-inositol (1, 2, 3, 4, 5, 6-hexakis dihydrogen phosphate)] is regarded as the primary storage form of phosphorus, and possibly inositol, in almost all grains or seeds. Although the presence of phytic acid in plant seeds has been known for over a century, its exact role in animal nutrition is not completely understood. However, it is considered an antinutritional factor because it forms insoluble complexes with proteins and several minerals (that is, Ca, Fe, Zn, Mn, Mg) to render them biologically unavailable (Cabahug et al., 1999). At neutral pH, the phosphate groups in phytic acid have either one or 2 negatively charged oxygen atoms, hence cations are able to chelate strongly between 2 phosphate groups or weakly with a single phosphate group. Phytate can also change Na partitioning and as a consequence may influence the capacity of the gut for Na-dependent transport of nutrients including glucose and peptides (Cowieson et al., 2009). The phytic acid content of CM is fairly high (Table 1). The proportion of phytate P in the total P content of Brassica meals ranges from 36 (Broz and Ward, 2007) to over 70% (Summers et al., 1983).

Phytase is an enzyme that hydrolyses phytic acid to inositol and inorganic phosphorus, leading to improved phosphorus utilization and overall growth performance of monogastric animals. Commercial phytases are produced by microorganisms such as *Aspergillus ficuum*, *Aspergillus niger*, *Escherichia coli*, *Pichia pastoris*, and others. Progress in recombinant DNA technology has resulted in the production of phytases with improved functional properties that would ultimately lead to cost savings in poultry feeding programs. Summaries of reports on the effects of phytase on growth performance and nutrient utilization of broiler chickens and laying hens have been recently published by Selle and Ravindran (2007), Singh (2008), Cowieson et al. (2009), and Slominski (2011). Kong and Adeola (2011) studied the effect of phytase supplementation (0 or 1,500 U/kg) and 3 levels of canola meal (125, 250, or 375 g/kg) on growth performance of broiler chickens. The main effect of phytase addition on BW gain was significant ($P < 0.05$) from d 15 to 22. However, phytase supplementation did not affect true ileal digestibility of amino acids. In another study (Józefiak et al., 2010), addition of phytase in combination with carbohydrase to the wheat-based diet containing full-fat canola improved growth performance and enhanced insulin liver receptor sensitivity in broilers.

Sinapine

Sinapine, a choline ester of sinapic acid, accounts for approximately 1% of CM and has been implicated with the production of a "fishy" taint in brown-shelled eggs (Butler et al., 1982). It has been found that the taint is due to the presence of trimethylamine (**TMA**) in the yolk, which results from a genetic defect among laying hens of Rhode Island Red breeding which are unable to convert TMA to the odorless N-oxide by liver or kidney TMA-oxidase. Trimethylamine may be produced from either sinapine or directly from choline by the action of microorganisms in the gastrointestinal tract. Fish meal, SBM, and certain vitamins or lecithins are also rich sources of choline for the hen. The TMA oxidase deficiency is not linked to the shell color, as has sometimes been supposed, given that it was found in Brown Leghorns whose eggs have white shells but was not present in a New Hampshire Red hybrid which lays brown eggs. Nevertheless, the White Leghorns have been reported not to be affected. Similarly, no taint or off-flavor has been detected in broiler carcasses. Progress has been made in identifying the genetic defect that leads to the production of tainted eggs (Honkatukia et al., 2005) and the elimination of this defect through breeding could be soon achieved (Newkirk, 2009).

Dietary Electrolyte Balance

Optimal dietary electrolyte balance is crucial for maximum broiler performance and livability (Saedi and Khajali, 2010; Khajali and Saedi, 2011). Canola meal contains less potassium than SBM (11.4 vs. 19.6 g/kg), so that the dietary electrolyte balance (**DEB**) or dietary cation-anion difference (**DCAD**) is much lower in CM compared with SBM (Table 2). Summers (1995)

Table 2. Mineral content of canola meal and soybean meal (10% moisture basis)

Mineral	Canola meal[1]	Soybean meal[2]
Ca (%)	0.67	0.33
P (%)	1.02	0.66
Na (%)	0.08	0.01
Cl (%)	0.10	0.05
K (%)	1.17	2.00
S (%)	0.65	0.44
Mg (%)	0.56	0.28
Electrolyte balance (mEq/kg) Na + K – Cl	307	504
Dietary cation-anion difference (mEq/kg) (Na + K) – (Cl + S)	103	366

[1]Average values calculated from Bell and Keith (1991); Newkirk (2009); Rogiewicz et al. (2012).
[2]NRC (1994).

indicated that broiler weight gain increased linearly when DEB increased from 50 to 150 MEq/kg. He also suggested that a DEB of 250 mEq/kg of diet would be optimal for maximum growth.

Canola meal is also low in sodium (Bell and Keith, 1991). March (1984) corrected the depression in growth performance of broilers fed a CM-based diet by increasing dietary NaCl content from 2.5 to 5 g/kg. In another study, feeding a CM-based diet with optimal DEB improved growth performance of broiler chickens (Mushtaq et al., 2007). Canola meal also contains more sulfur than SBM (0.65 vs. 0.44%). It is well known that high levels of sulfur in CM could cause leg abnormality in broiler chickens due to sulfur interference with calcium absorption (Summers et al., 1990, 1992; Summers, 1995). It has also been demonstrated that sulfur from inorganic sources (that is, sulfuric acid) would be more toxic than that from an organic source such as cysteine (Summers et al., 1990). However, feeding of excess sulfur in organic form would also result in incidence of leg problems. Approximately 75% of the total sulfur in SBM exists in organic form (that is, sulfur amino acids), whereas for CM it is around 60%. It has been documented that GLS in CM are partially responsible for high incidence of leg problems, especially tibial dyschondroplasia. Supplementing with extra calcium would help to minimize the problem, but care must be taken because too much dietary calcium may depress feed intake. Work by Summers and Bedford (1994) showed that when the total DEB is considered, the higher sulfur level in CM would result in an even lower positive balance of dietary cations. Because feed intake in broilers is positively correlated with DEB, the commonly observed decrease in feed intake when including CM in broiler feeds could be related to the cation and anion levels in the diet. This further suggests that increasing levels of dietary cations will correct the problem. Attempts should be made to supplement potassium carbonate to CM-based diets to overcome the problems associated with the reduced feed intake (Newkirk, 2009; Khajali et al., 2011). The selection pressure by plant breeders to further reduce the GLS content of canola would also result in the reduced sulfur content of the meal, which would ultimately improve the DEB.

Metabolizable Energy

Canola meal is known for having a lower metabolizable energy (**ME**) content than that of SBM (Table 1). Distinct differences in chemical composition of these 2 feed ingredients do not make it possible to exactly pinpoint the components responsible for such a difference. Both protein supplements contain similar amounts of sugars (0.6%), starch (2.0%), and relatively high amounts of sucrose (6%; Table 1). Soybean meal is higher in oligosaccharides (5.6 vs. 2.0%), which when converted to short-chain fatty acids by microbial population of the lower gut may contribute to the overall energy content of this ingredient. However, CM is significantly higher in fat content, which should minimize the difference in ME content between the 2 ingredients. A recent survey involving 11 crushing plants across Canada (Rogiewicz et al., 2012) demonstrated, however, that the level of fat (ether extract) in the meal could be as low as 1.4% (10% moisture basis) and as high as 4.3%, with the average value of 3.3%. This would be a consequence of different processing practices among the plants in terms of adding back any by-products of oil refining (i.e., gums, phospholipids) into the meal (Newkirk, 2009). Such practices and the source of CM used in different studies could have significant repercussions in ME determination. The higher protein and lower fiber contents of SBM could further contribute to the difference in the ME content between the 2 meals. The main reason for the lower ME of CM may be explained by the fact that the high dietary fiber content may accelerate the digesta passage rate, which in turn, may result in reduced time for digestion and thus reduced nutrient utilization.

Amino Acid Composition and Digestibility

The most valuable component of CM is its protein with a well balanced amino acid composition. When compared with SBM (Table 1), CM has less lysine but more sulfur-containing amino acids. Canola meal is known for its lower and less consistent amino acid digestibility than SBM. The reason for the reduced digestibility is, at least in part, related to processing conditions. It is well known that overheating of oilseed

meals during processing can lead to losses in the content and digestibility of amino acids (Parsons et al., 1992). Research has shown that apparent digestibility of lysine in canola decreased by 5% during the solvent extraction process (from 0.85 to 0.80; Anderson-Hafermann et al., 1993). This suggests a potential negative effect of the desolventization process, which includes meal toasting. Likewise, Newkirk et al. (2003) found similar results. In their study, apparent lysine digestibility coefficient was significantly reduced (from 0.87 to 0.79) in desolventized and toasted CM. Formation of Maillard reaction products during meal desolventization along with the glycoproteins associated with the cell wall structure are both responsible for the total protein digestibility figure of 80 to 85% (NRC, 1994). This highly indigestible fraction, often referred to as neutral detergent insoluble nitrogen (**NDIN**), accounts for 10% or more of the total protein content of CM. Newkirk et al. (2000) used NDIN as a measure of CM protein and amino acid digestibility and documented that NDIN values below 10% indicate a CM with greater than 85% lysine availability. In the study by Huang et al. (2005), the digestibility of amino acids in both CM and SBM was found to be age-dependent. Higher amino acid digestibility values were reported for broiler chickens at 42 d of age than for those at 14 d of age, with the most pronounced difference observed for threonine (0.72 vs. 0.69) and arginine (0.88 vs. 0.85). These differences in amino acid digestibility can be significant in practical feed formulation when high inclusion levels of CM are used.

Arginine (**Arg**) content of CM is approximately two-thirds of that of SBM (2.04 vs. 3.23%; Table 1). Likewise, essential amino acid digestibility values of CM are lower than those of SBM (Heartland Lysine, 1998). Substitution of a high proportion of CM protein at the expense of SBM protein in poultry diets may drop dietary Arg level below its requirements and subsequently result in poor performance (Izadinia et al., 2010). Synthetic Arg is not commercially available and thus not used as a dietary supplement. Chickens fail to synthesize Arg because they lack the key enzyme carbamoyl phosphate synthase I (EC 6.3.5.5) and have low activities of hepatic arginase (EC 3.5.3.1., 2) and ornithine transcarbamoylase (OTC, EC 4.4.4.17). Therefore, they have an absolute need for Arg and are highly dependent on dietary sources for this amino acid (Khajali and Wideman, 2010). In addition, Arg has been documented to be the precursor of nitric oxide, a potent vasodilator (Collier and Vallance, 1989). Studies with broiler chickens fed CM-based diets indicated that dietary Arg content may not be adequate to fully support the production of nitric oxide (NO) by avian macrophages and the pulmonary vascular epithelium (Wideman et al., 1995; Izadinia et al., 2010). Diminished NO availability and production has been implicated in the pathogenesis of pulmonary hypertension and in other vascular disorders including atherosclerosis (Shaul, 2002). Substitution of CM for SBM in relation to pulmonary hypertension and ascites in broiler chickens has been recently documented by Izadinia et al. (2010). They raised broiler chickens at a high-altitude area (2,100 m above sea level) and fed diets substituted with 0, 50, and 100% of CM for SBM. Their findings showed that feeding the CM diets resulted in poor growth performance and predisposed the birds to pulmonary hypertension and ascites. Khajali et al. (2011) supplemented a CM diet with different levels of Arg and observed a linear increase in growth performance and plasma NO levels with concomitant decrease in pulmonary hypertension and mortality due to ascites. Basoo et al. (2012) re-evaluated the Arg requirements for broilers raised at high altitude during the 3- to 6-wk period. They estimated that Arg requirement for maximal growth and reduced pulmonary hypertension was 20% higher than that of the NRC (1994) recommendation (1.32 vs. 1.1% of diet). It would appear that supplementation of Arg to broiler diets at high altitude regions is necessary even in circumstances when the diets are composed of SBM. A recent report indicated that under optimal rearing conditions, supplementation of 1% Arg to broiler diets comprised of SBM significantly increased the plasma concentration of NO (Ruiz-Feria, 2009). Kidd et al. (2001) reported that supplementing broiler diets with 0.2% Arg beyond NRC (1994) requirements resulted in improved growth performance under normal rearing conditions. Table 3 depicts a summary of some results on dietary Arg supplementation to broiler diets.

In conclusion, attention must be drawn toward dietary Arg level when high amounts of CM are used

Table 3. Response of broiler chickens to dietary L-arginine supplementation

Diet	Trial length (d)	BW gain (kg/bird)	FCR[1] (g of feed/g of gain)	Plasma nitric oxide (μmol)	Ascites mortality (%)	Reference
Corn-canola meal (C-CM)	1–42	1,690[b]	2.29[a]	26.3[b]	16.0[a]	Khajali et al., 2011
C-CM + 0.2% L-arginine		1,733[ab]	2.29[a]	43.1[a]	14.7[ab]	
C-CM + 0.4% L-arginine		1,781[a]	2.25[a]	45.1[a]	10.7[b]	
Corn-soybean meal (C-SBM)	1–18	505.8[b]	1.44[a]	—	—	Kidd et al., 2001
C-SBM + 0.2% L-arginine		547.2[a]	1.40[a]			
Corn-soybean meal (C-SBM)	1–42			6.7[b]	—	Ruiz-Feria, 2009
C-SBM + 1% L-arginine				10.2[a]		

[a,b]Means within a column with no common superscripts differ significantly ($P < 0.05$).

[1]FCR = feed conversation ratio.

in broiler diets especially in situations where partial pressure of oxygen is low (that is, high altitude, poor ventilation, cold conditions).

IMPROVEMENTS TO THE NUTRITIVE VALUE OF CANOLA MEAL

Various approaches have been undertaken in an attempt to reduce the fiber content, increase the protein content, and to improve the overall nutritive value of CM. These include breeding for low-fiber, yellow-seeded canola, removal of the hull before oil extraction, or the use of microbial enzymes to enhance nutrient utilization by rapidly growing monogastric animals.

Development of Low-Fiber, Yellow-Seeded Canola

Selection for yellow seed coat color, a visual marker of lower polyphenol content, has been a priority in plant breeding in an attempt to reduce the fiber content of the meal. A negative correlation between the presence of ADF and NDF and both protein and oil in the seed has been reported (Rashid and Rakow, 1999). Yellowness of seeds, which is thought to be associated with a reduction of proanthocyanidin content and the thinner seed coat, represents a major agronomic trait for *Brassica* crop improvement. Indeed, the yellow-seed trait is linked to increased seed oil content and lower dietary fiber content (Slominski et al., 1999).

Earlier research has shown yellow-seeded *B. napus* canola to have superior quality characteristics to that of yellow-seeded *B. rapa*, *B. juncea*, and the black-seeded type of *B. napus*, both in terms of chemical composition (i.e., lower fiber, lower phytate phosphorus, lower GLS, and higher protein content) and the overall nutritive value as determined with broiler chickens (Simbaya et al., 1995; Slominski, 1997).

Since the first observation on the existence of the yellow-seeded characteristic in progenies of resynthesized *B. napus*, only recently have plant breeders been able to develop a fully yellow-seeded and high-yielding line of *B. napus* from interspecific crosses between yellow-seeded *B. juncea* and *B. carinata* and black-seeded *B. napus* (Rashid and Rakow, 1999).

Canola breeding programs undertaken at the Saskatoon Research Centre, Agriculture and Agri-Food Canada has also led to the development of canola quality (low glucosinolate, low erucic acid) forms of *B. juncea*, a species known for its pure yellow seed coat. Under Western Canadian conditions, *B. juncea* suffers less from heat and drought stress and matures earlier than *B. napus*. Such characteristics are the basis for high yields of oil and low chlorophyll content in the seed.

At the 2011 Rapeseed Congress in Prague (Smulikowska et al., 2011; Wittkop et al., 2011), it became evident that plant selection programs directed toward development of yellow-seeded *B. napus* canola have been underway in some other countries including Germany and Poland.

In the recent study from Canada (Slominski et al., 2011), the chemical and nutritive composition of meals derived from black- and yellow-seeded *B. napus* canola and canola-quality *B. juncea* were evaluated (Table 4). In comparison with its black-seeded counterpart, meal derived from yellow-seeded *B. napus* canola contained more protein, more sucrose, and less dietary fiber and glucosinolates. Lower fiber content in yellow-seeded *B. napus* canola was reflected in lower content of lignin with associated polyphenols (3.7 vs. 7.1% DM). *Brassica juncea* canola showed intermediate levels of crude protein, sucrose, and dietary fiber. A seed fractionation study demonstrated that the reduction in fiber content of yellow-seeded *B. napus* is a consequence of a bigger seed size, a lower contribution of the hull fraction to the total seed mass, and a lower lignin/polyphenol content of the hull fraction. Although somewhat lower in lysine and methionine (when expressed in g/16 g of N), yellow-seeded *B. napus* CM contains significantly higher amounts of Arg than its black-seeded counterpart.

The nutritive value of the meals was investigated with broiler chickens fed corn-based diets containing 30% of CM (Slominski et al., 2011). Significantly higher ($P < 0.05$) lysine (87.9%), methionine (89.1%), threonine (82.2%), and total ileal digestibility of amino acids (87.3%) were observed in birds fed the yellow-seeded *B. napus* diet when compared with those fed diets containing black-seeded *B. napus* (85.5, 87.9, 77.4, and 84.1%, respectively) or *B. juncea* canola (83.1, 87.3, 76.5, and 83.8%, respectively). The AME_n values for yellow- and black-seeded *B. napus* and *B. juncea* as determined with broiler chickens were 2,190, 1,904, and 1,736 kcal/kg of DM, respectively. In the assay with turkeys, the AME_n values for yellow- and black-seeded *B. napus* and *B. juncea* canola were of the same order of magnitude to those determined with broiler chickens (Table 4). The reasons for low available energy content of *B. juncea* meal are not clear and are discussed in the recent publication from this laboratory [W. Jia (University of Manitoba, Winnipeg, MB, Canada), D. Mikulski (University of Warmia and Mazury, Olsztyn, Poland), A. Rogiewicz (University of Manitoba, Winnipeg, MB, Canada), Z. Zdunczyk (Institute of Animal Reproduction and Food Research, Polish Academy of Sciences, Olsztyn, Poland), J. Jankowski (University of Warmia and Mazury, Olsztyn, Poland), and B. A. Slominski, unpublished data].

Zdunczyk et al. (2011) evaluated the physiological response of young turkeys (from 21 to 30 d of age) to diets containing meals derived from black- and yellow-seeded *Brassica napus* canola and *B. juncea*, which served as the only source of protein and energy in the diets (93%). In comparison to black-seeded *B. napus*, feeding the diet containing meal derived from yellow-seeded *B. napus* canola resulted in a lower pH of the small intestinal contents, an increased mass of cecal

Table 4. Chemical composition of meals derived from black- and yellow-seeded *Brassica napus* canola and canola type *B. juncea* (% DM)[1]

Item	*B. napus* black	*B. napus* yellow	*B. juncea*
CP	43.8[c]	49.8[a]	47.4[b]
Fat	1.8[b]	1.6[b]	1.7[b]
Ash	7.3[a]	7.0[b]	7.2[a]
Carbohydrates			
Monosaccharides[2]	0.2[b]	0.3[a]	0.3[a]
Sucrose	8.8[c]	10.2[a]	9.2[b]
Oligosaccharides[3]	3.1[b]	2.5[c]	3.6[a]
Starch	0.4	0.4	0.3
Dietary fiber components			
Nonstarch polysaccharides	20.2[a]	18.7[b]	20.0[a]
Lignin and polyphenols	7.7[a]	4.0[c]	4.2[b]
Glycoproteins	2.1[a]	1.5[c]	1.7[b]
Total fiber	30.1[a]	24.1[c]	25.8[b]
Amino acids (g/16 g of N)			
Lysine	6.1[a]	5.7[b]	5.3[c]
Arginine	5.7[b]	6.3[a]	6.4[a]
Methionine	2.1[a]	1.9[b]	2.0[b]
Threonine	4.3	4.3	4.3
Total amino acids	91.3[b]	94.4[a]	92.7[ab]
Glucosinolates[4] (μmol/g)	30.7[a]	20.0[b]	18.8[c]
ME (kcal/kg)			
Broiler chickens	1,904[a]	2,190[a]	1,737[a]
Turkeys	2,007[b]	2,166[a]	1,877[b]

[a–c]Means within a row with no common superscripts differ significantly ($P < 0.05$).

[1]Adopted from Slominski et al. (2011).

[2]Includes glucose and fructose.

[3]Includes raffinose and atachyose.

[4]Includes gluconapin, glucobrassicanapin, progoitrin, gluconapoleiferin, glucobrassicin, and 4-hydroxyglucobrassicin.

contents, and a decreased concentration of short-chain fatty acids. Feeding yellow-seeded *B. juncea* meal, on the other hand, caused more significant changes in the intestinal function, including lower hydration and higher viscosity of the small intestinal contents and increased bacterial α- and β-glucosidase, α-galactosidase, and β-glucuronidase activities in the ceca. The physiological responses of turkeys fed meals from low- and high-fiber canola may be explained by the fact that the high dietary fiber content may accelerate the digesta passage rate, which in turn, may result in reduced time for digestion and thus reduced nutrient utilization.

It would appear evident that the meal derived from yellow-seeded *B. napus* canola would have superior quality characteristics to those from black-seeded *B. napus* or yellow-seeded *B. juncea* canola.

Dehulling

Another promising route in reducing fiber content is removal of the hull before oil extraction. When evaluating the meals from the dehulling process conducted at the POS pilot plant in Saskatoon, Canada (Simbaya et al., 1992), a significant increase in protein content of the dehulled versus standard meal (47.2 vs. 40.8%) and a substantial reduction in the content of 2 major components of dietary fiber: NSP (14.7 vs. 18.1%) and lignin with associated polyphenols (4.3 vs. 7.7%) was observed. In a similar study using a dehulled meal from the SKET GmbH Magdeburg, Germany pilot plant, Kracht et al. (2004) reported that dehulling yielded a significant decrease in crude fiber content by 40%, ADF by 35%, and NDF by 28%, which were followed by an increase in protein content by 7% points. Although it is believed that the utilization of CM will be improved with hull removal, as yet, a few obstacles disallow implementation of the dehulling process by the canola crushing industry. Among them, losses of oil during the dehulling process and excessive fineness of the meal and thus difficulties with percolation of the miscella through the cake appear critical.

Enzymes

Application of dietary enzymes, including phytase, protease, and carbohydrases, to facilitate phosphorus, protein, and energy utilization is among other approaches to quality improvements of CM (Slominski and Campbell, 1990; Simbaya et al., 1996; Kocher et al., 2000). Most studies to date examined the use of NSP-degrading enzymes in an attempt to improve carbohydrate digestibility and to eliminate any potential nutrient encapsulating effect of cell wall NSP. A combination of cell wall-degrading enzymes has been developed (Meng et al., 2005) and proven to be effective in improving the nutritive value of canola seed-containing diets for broiler chickens (Meng et al., 2006; Józefiak et al., 2010) and laying hens (Jia et al., 2008). Such studies are a consequence of a growing interest within the feed industry to use full-fat canola or off-

Table 5. Effect of enzyme supplementation on total tract nonstarch polysaccharide (NSP) and fat digestibilities and on energy utilization in adult roosters and broiler chickens (Meng et al., 2006)

Birds/diet type	BW gain (g/bird per day)	FCR[1] (g of feed/g of gain)	Digestibility (%)		AME_n (kcal/kg)	TME_n[2] (kcal/kg)
			NSP	Fat		
Adult roosters (TME assay)						
Canola seed (control)	—	—	4.4[b]	63.5[b]	—	3,642[b]
Canola seed + enzyme[3]	—	—	25.8[a]	79.3[a]	—	4,761[a]
Broiler chickens (5–18 d)						
Corn-SBM[4]-canola seed (control)	497	1.41[a]	10.5[b]	69.6[b]	2,963[b]	—
Corn-SBM-canola seed + enzyme[3]	506	1.37[b]	21.0[a]	77.5[b]	3,165[a]	—

[a,b]Means within a column with no common superscripts differ significantly ($P < 0.05$).

[1]FCR = feed conversion ratio.

[2]TME_n = true metabolizable energy.

[3]Contained pectinase, cellulase, xylanase, mannanase, galactanase, and glucanase as main activities.

[4]SBM = soybean meal.

grades of canola seed as they represent an economic, well-balanced source of protein (22%) and oil (45%). In addition to providing a considerable amount of energy, the oil of canola seed is an excellent source of α-linolenic acid (18:3ω3; 10%), which along with its derivatives eicosapentaenoic acid (**EPA**, $C_{20:5\omega3}$) and docosahexaenoic acid (**DHA**, $C_{22:6\omega3}$) deposited into the eggs or meat products has been shown to be important for human health (Hargis and Van Elswyk, 1993). However, the energy utilization from ground canola seed has been demonstrated to be lower than that of the corresponding CM and canola oil mixture (Lee et al., 1991; Meng et al., 2006) due to the oil-encapsulating effect of the cell wall NSP. As illustrated in Table 5, poorer ($P < 0.05$) FCR, lower total tract NSP and fat digestibilities, and lower true metabolizable energy (**TME_n**) and AME_n contents were observed for the control canola seed diets. Enzyme supplementation resulted in the improvement ($P < 0.05$) in NSP and fat digestibilities and TME_n and AME_n contents in broiler chickens and adult roosters (Meng et al., 2006). These data are a clear indication of the need for multicarbohydrase enzyme supplements in poultry diets containing full-fat canola.

The effect of cell wall-degrading enzymes was also studied in diets containing CM. However, as reported by Meng and Slominski (2005), only a trend ($P < 0.096$) in improved AME_n content was noted with enzyme supplementation even though the digestibility of NSP increased significantly ($P < 0.05$) from 7.6 to 16.9% in birds fed the enzyme-supplemented CM diet. Similar results were observed earlier by Simbaya et al. (1996), Kocher et al. (2000), and Mushtaq et al. (2007) when using less diversified cocktails of enzyme activities. This is understandable given that, as opposed to canola seed in which case the degradation of the cell wall structure results in the release of a significant amount of oil, NSP degradation in the CM-containing diets would only contribute to the increase in NSP hydrolysis products, which when utilized will not generate as much energy as that derived from fat. In this context, it is important to note that CM is lacking any oil-containing cells due to their effective rupture during the prepress solvent extraction process. However, when evaluating the effect of enzyme in diets containing CM along with other high-fiber ingredients, the beneficial effect of enzyme supplementation could be more pronounced due to more substrate (fiber) available for hydrolysis. The results of a broiler chicken study conducted to validate the effects of multienzyme addition to a diet containing CM, canola screenings and other high-fiber ingredients are shown in Table 6. Growth performance, as measured by BW gain and FCR, was depressed ($P < 0.05$) in birds fed the negative control (**NC**) diet as compared with those fed the positive control (**PC**) diet. However, enzyme addition to the NC diet eliminated

Table 6. Growth performance, DM, and nonstarch polysaccharide (NSP) digestibilities and AME_n content in broiler chickens (1–37 d) fed a positive control diet (PC) and the nutrient deficient negative control diet (NC) without and with enzyme supplementation (Boros et al., 2004)

Diet	BW gain (kg/bird)	FCR[1] (g of feed/g of gain)	Digestibility (%)			AME_n (kcal/kg of diet)
			DM	NSP	Phytate	
Wheat-soybean meal-fish meal (PC)	2.14[a]	1.68[b]	71.2[b]	4.8[b]	44.3[b]	2,954[a]
Wheat-barley-canola meal-soybean meal-canola screenings (NC)	2.10[b]	1.76[a]	68.7[b]	15.0[b]	37.5[c]	2,825[b]
NC + enzyme[2]	2.17[a]	1.66[b]	75.1[a]	36.1[a]	69.5[a]	3,067[a]

[a–c]Means within a column with no common superscripts differ significantly ($P < 0.05$).

[1]FCR = feed conversion ratio.

[2]Contained pectinase, cellulase, xylanase, mannanase, galactanase, and glucanase as main activities.

the growth depressing effect such that performance was equal among the PC and NC diets. The significant improvement in broiler chicken performance with enzyme supplementation was further substantiated by the same magnitude of difference in DM and NSP digestibilities and energy (AME) utilization. It is of interest to note that although the enzyme phytase was not included in the enzyme cocktail used in this study, the digestibility and thus utilization of phytate P was high and most likely resulted from the increased efficacy of intrinsic phytase of feed ingredients due to elimination of the phytate chelating effects of NSP by the NSP enzymes (Slominski, 2011).

In light of new developments in canola breeding (see Development of Low-Fiber Canola section in this review), it has been demonstrated that the multicarbohydrase enzyme addition to broiler chicken diets containing meals derived from black-seeded and yellow-seeded *B. napus* and canola type *B. juncea* mustard increased energy (AME) utilization from 1,943 to 2,249 kcal/kg of DM (on average), with the most pronounced effect observed for *B. juncea* canola (from 1,736 to 2,356 kcal/kg of DM; Slominski et al., 2011). It would appear that the response of *B. juncea* meal to enzyme supplementation could result from elimination of the viscous properties of mucilage, the nonstructural polysaccharide common for mustard species.

The low-fiber, yellow-seeded canola has shown advantages for its higher protein and total amino acid contents, especially arginine, lower fiber, and lower glucosinolate and polyphenol levels when compared with its black-seeded counterpart. Application of enzymes has shown to increase the energy utilization and the nutritive value of CM for poultry

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