Contribution of exogenous enzymes to the preservation of limited feed resources

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Summary

Exogenous enzymes have been used commercially for 20 years. Supplementation of monogastric animal diets with enzymes enables better utilisation of the nutrients in feedstuffs. The benefits of this practice are multiple. Feed costs are reduced because of better utilisation of low cost and, ideally, indigenous raw materials. Variation in animal response is reduced because of less variation in nutrient availability between ingredient batches. There are also environmental benefits associated with reduced excreta outputs. The feed industry is currently faced with new challenges and will need to adapt to economic and regulatory changes. In this context, enzymes are an alternative way of optimising the utilisation of feed resources. This review discusses recent trends in raw material supply and factors affecting the nutritive value of cereal grains and their by-products, legume seeds and protein meals, and shows how exogenous enzymes can be used to improve both the quality and value of feed.

Keywords: enzymes, monogastric, cereals, legumes, cereal by-products

Introduction

Recent economic pressures and increased concerns about environmental protection have resulted in changes in paradigms within the animal feed industry. Nutritionists are currently more aware than ever of the need to reduce costs and preserve natural resources. Consequently, there is now greater reliance on locally-grown crops to limit imports and decrease the carbon footprint associated with transport. The development of the biofuel industry has also affected the availability of ingredients for animal diets. Utilisation of vegetable protein sources is now increasing because of the relatively high price of animal protein and legislative control measures (e.g., the ban on meat-and-bone meal in some countries). The use of exogenous enzymes has become more attractive because of these changes. Enzyme-mediated improvement of diet digestibility has a direct effect on the amount of feed required to satisfy nutrient requirements and on manure output. For example, improvement of digestibility from 85% to 90% results in a 5% reduction in the amount of feed required and a 33% reduction in faecal output. In addition, the use of enzymes may render low quality protein sources more competitive. Protein digestibility may be improved by up to five percentage points and faecal nitrogen and organic matter output may be reduced by as much as 20% by enzyme treatment of diets (FAO, 1994).

Current and future trends in global grain, grain by-product and vegetable protein supply

The availability of ingredients for animal diets is dependent on crop plantings and yields. Local availability is dependent on the relative demand for and distribution of crop commodities between the production of human food, industrial commodities and animal feed.

According to the USDA (www.usda.gov), the total grain production for 2008/09 is estimated to be 2225 million tonnes, 4.8% and 11.0% more than for 2007/08 and 2006/07, respectively. Wheat production should reach 684 million tonnes in 2008/09, 12% more than that of the previous harvest year. Significant reductions in grain production in Argentina (–94%) and Kazakhstan (–33%) have been compensated by increases in grain production in the EU (+27%), Canada (+43%) and Australia (+54%). Animal feed production is projected to increase from 94 million tonnes in 2007/08 to 120 million tonnes in 2008/09. The production of coarse grains (maize, sorghum, barley, oats, rye and millet) is projected to be similar to that of the previous season (1100 million tonnes in 2008/09 vs 1080 million tonnes in 2007/08). Maize production is estimated to be 787 million tonnes in 2008/09, less than 1% lower than that of 2007/08. However, the use of maize for animal feed production will decrease from 496 million tonnes in 2007/08 to 477 million tonnes in 2008/09. Rice production is projected to be 441 million tonnes for 2008/09, 2.1% greater than that for 2007/08. Finally, the use of barley for animal feed production in 2008/09 is expected to increase by 11% compared with that of the previous year.

In the near future, animal diets will probably contain less by-products from the milling industry (wheat bran, rice bran and maize gluten) but more by-products from the biofuel industry (distiller's dried grains with solubles [DDGS] and glycerol). For the past few years, the shift in the market demand for cereals for the production of fuel instead of animal feed has resulted in a greater availability of by-products for the animal feed industry. The USDA reported that for the 2006/07 crop year, 53 million tonnes of US maize was used to produce ethanol. For 2008/09, it is estimated that 91 million tonnes of US maize will be used in bio-ethanol plants. This represents approximately 30% of the total US maize crop. According to the Agricultural Marketing Resource Centre (www.agmrc.org), DDGS production in the USA is expected to increase from 26 million tonnes in 2007/08 to 34 million tonnes in 2008/09. Exports should follow the same trend, from 4 to 6 million tonnes. A similar trend is expected to occur in Europe, where there will be a significant increase in the availability of DDGS, mainly from wheat. More than 7 million tonnes of wheat DDGS are predicted to be produced in 2010. The use of other grains (e.g., barley and sorghum) for ethanol production remains limited.

The world market of protein-rich ingredients is increasing continuously, and was 250 million tonnes in 2007/08. Soybean meal is still the main source of vegetable protein, but the use of rape seed/canola is increasing. In Europe, estimates show that there will be a change in the availability of protein sources in the future: less soybean meal and sunflower meal but more rape seed meal. According to the USDA (www.usda.gov), oilseed production for 2008/09 is projected to be 408 million tonnes, 4% higher than that produced in 2007/08, but similar to that produced in 2006/07. The production of oil meals should reach 231 million tonnes in 2008/09, a level similar to that of 2007/08. Vegetable oil production in 2008/09 is estimated to be 133 million tonnes, 2.3% more than that in 2007/08.

Nutritional value of cereal grains and their by-products from the milling industry in monogastric animal diets

Like other raw materials derived from plants, cereal grains are complex structures in which a range of nutrients interact with each other via chemical or physical associations. These interactions, as well as the concentration of each nutrient, determine the nutritive quality of the grain as an animal feedstuff.

Wheat (*Triticum aestivum*) and wheat by-products

Wheat and its by-products are major ingredients in monogastric diets. As with other cereals, the composition of wheat is determined by genetics and growing conditions. As more than one hundred wheat cultivars are used worldwide, the nutrient content of wheat varies. Kim (2003) showed that among 426 samples of wheat, the content of crude protein (CP) varied from 9.1–22.8%, that of starch varied from 50.4–79.5% and that of non-starch polysaccharides (NSPs) varied from 7.5–16.6%. Arabinoxylans are the main components of fibre in wheat and account for 88% and 65% of the endosperm and aleurone cell-walls, respectively. The total phosphorus (P) content of wheat is 0.31%, of which phytate P constitutes 65–75% (Selle et al., 2003; Tran and Skiba, 2005). Wheat is also characterised by relatively high endogenous phytase activity. Wheat by-products such as wheat bran and wheat middlings are composed mostly of the outer layers of the grain. Compared with whole grain, these by-products have higher NSP and CP contents and lower starch content.

The nutritional value of wheat depends on its total nutrient content and digestibility (Carré et al., 2007). As shown by Carré et al. (2005), the total nutrient content of grains is negatively correlated with cell-wall content. Thus, cultivars with high fibre content generally have a low energy value. For poultry, the metabolisable energy (ME) content of wheat varies from 8.5–15.9 MJ/kg dry matter (DM) when the diet contains more than 75% wheat (Mollah et al., 1983; Rogel et al., 1987). This variation is mainly associated with variation in the digestibility of lipid and starch. The major part of the variation in lipid digestibility is attributed to viscosity problems because of the presence of soluble arabinoxylans (Choct and Annison, 1992; Maisonnier et al., 2001). The variation in starch digestibility is also associated with physical parameters. There is a negative relationship between starch digestibility and grain hardness (hardness value and mean particle size) (Carré et al., 2002; Carré et al., 2005; Péron et al., 2006). This effect is most likely because hard grains result in more coarse particles in the gut, which reduces access of endogenous enzymes and microbes to starch granules (Péron et al., 2005, 2007). Finally, it is important to note that a significant part of the variation in the ME content of wheat for broilers is associated with the genetic ability to digest wheat (Mignon-Grasteau et al., 2004). The digestible energy (DE) content of wheat for pigs varies from 13.7–17.0 MJ/kg DM when the diet contains up to 95% wheat (van Barneveld, 1999). The DE content of wheat by-products tends to be lower and more variable than that of wheat grain. Batterham et al. (1980) reported that the DE content of wheat by-products ranged from 10.9–14.1 MJ/kg DM. This variation is caused by differences in the milling process, which results in variation in the ratio between the bran and residual endosperm or germ fractions. Unlike broilers, starch digestion is not a major problem in growing pigs. Energy digestion and nutrient utilisation are mainly dependent on the NSP component, especially the hemicellulose fraction (van Barneveld, 1999; Zijlstra et al., 1999; Kim, 2003). The hemicellulose fraction of wheat is mostly composed of insoluble arabinoxylans. In pigs, the negative effect of soluble NSPs (i.e., viscosity) is less than in growing birds, but the insoluble NSPs cause other anti-nutritive effects. High dietary levels of insoluble NSPs result in increased water-holding capacity, slower transit time, reduced access for digestive enzymes (nutrient packaging) and increased endogenous secretions

(Partridge, 2001). All these effects have a negative effect on nutrient and energy digestion and may also result in bacterial proliferation in the gut (Partridge, 2001).

Barley (*Hordeum vulgare*)

Barley is grown for many purposes, but most is used for animal feed production, human consumption, or malting. Analysis of a large number of barley samples by Holtekjølen et al. (2006) showed that starch is the major constituent of barley (51.3–64.2%), followed by NSPs (22.6–41.1%), whereas CP accounts for only 8.2–18.5%. The major fibre components of barley are β-glucans and arabinoxylans, which are mainly located in the endosperm cell walls and the aleurone layer. The amount of soluble NSPs in barley is two to five times higher than in wheat (Choct, 2006; Holtekjølen et al., 2006). Svihus et al. (2000) reported viscosity values for several wheat and barley samples derived using various assay methods and showed that the viscosity of barley was five times higher than that of wheat. Therefore, NSPs represent the main anti-nutrients in barley grain. The total P level of barley is similar to that of wheat. However, the proportional contribution of phytate P to total P is lower in barley than in wheat, indicating that P is more available in barley than in wheat. Barley also has relatively high endogenous phytase activity (Selle et al., 2003; Tran and Skiba, 2005).

The ME content of barley for poultry varies from 11.6–13.8 MJ/kg DM (Choct et al., 2001). This variation is mostly associated with variation in lipid digestibility because of the presence of soluble pentosans (Classen et al., 1995). The digestibility of protein and starch also varies, but to a lesser extent. The DE content of barley for pigs varies from 12.4–15.9 MJ/kg DM (van Barneveld, 1999). As with wheat, the interaction between starch granules and the protein matrix in the endosperm, which is closely associated with grain hardness and affects the particle size of ground barley, affects the nutritional value of barley. Studies with ruminants have shown a negative relationship between particle size and the digestibility of barley (Bowman et al., 1996; Surber et al., 2000). Soft barley cultivars are preferred by the malting industry because of a low degree of adhesion between starch granules and the surrounding protein structures.

Maize (*Zea mays*) and maize by-products

Despite an increase in the number of crops grown for the bio-ethanol industry, maize remains the most abundant cereal in animal diets. Maize has a low CP content (8%) compared with wheat and barley (12% and 11%, respectively). However, its energy value is higher than that of barley and wheat because of its higher starch level (64%) and lower NSP content (9.5%). The main fibre components in maize are arabinoxylans but, unlike wheat, maize contains very little soluble NSPs (Choct, 2006). Total P and phytate P levels are lower in maize than in wheat, but the ratio of phytate P to total P is higher, indicating that the bioavailability of P is lower in maize than in wheat. Moreover, endogenous phytase activity in maize grain is limited (Selle et al., 2003; Tran and Skiba, 2005).

Although the chemical composition of maize is favourable for inclusion in poultry diets, its nutritional value can vary substantially from batch to batch (D'Alfonso, 2002); ileal digestible energy varies by 2.04 MJ/kg DM. Analysis of USA maize samples from the same harvest year showed that ME values ranged from 12.2–14.5 MJ/kg (Leeson et al., 1993). This variation cannot be attributed to viscosity; Cowieson (2005) suggested that it was caused by variation in starch digestibility. Analysis of 220 samples showed that despite limited variation in starch content (2%), variation in the in vitro digestibility of maize starch was high (16%). The grain drying process can also affect the digestion of maize in broilers (Kaczmarek et al., 2008). High temperatures damage the structure of grain proteins, resulting in greater cohesion between starch granules and the protein matrix, which reduces starch hydrolysis by limiting enzyme accessibility. Cowieson (2005) also emphasized the importance of phytate content, as it may affect starch digestion through the formation of tertiary complexes with starch or binary complexes with calcium, a cofactor required for alpha amylase activity. There are relatively few studies on variation in the nutritive value of maize for pigs. As for poultry, maize is perceived to be of high and consistent nutritional value, and most studies have involved comparisons between maize varieties bred for improved economic value (e.g., low phytate varieties) (Partridge, 2001). However, early data reported by Leigh (1994) indicated that variation in maize quality was greater than expected. In piglets, particle size is associated with maize quality (Healy et al., 1994), suggesting that enzyme accessibility may be associated with differences in endosperm starch–protein interactions or cell-wall composition.

Maize by-products are also used by the animal feed industry. Besides DDGS, maize gluten feed and maize gluten meal are widely used in the animal feed industry, whereas the use of maize bran (also known as corn mix) is limited. Maize gluten meal and maize gluten feed are products of the wet-milling industry. Maize gluten feed is a mixture of bran, oil-extracted germ and residual gluten and starch fractions. It is has a moderately high CP content (20–25%) and exhibits high variation in amino acid digestibility and ME (Sibbald, 1986; Castanon et al., 1990). In contrast, maize gluten meal has a high protein concentration (40–60%) and is highly digestible.

Sorghum (*Sorghum bicolor*)

The structure and chemical composition of sorghum is similar to that of maize. The CP content of sorghum is slightly higher than that of maize and ranges from 7–13%. The average starch and total NSP contents are 65% and 12%, respectively. Most of the NSPs in sorghum are insoluble and consist mainly of arabinoxylans. Some uronic acids are also present. The total P content of sorghum is similar to that of wheat and barley but, like maize, the ratio of phytate P to total

P is high, indicative of low P bioavailability (Selle et al., 2003; Tran and Skiba, 2005). Sorghum differs from other grains such as maize and wheat in that some cultivars contain high levels of tannins. Tannins have been associated with numerous deleterious effects: decreased performance and digestibility, inhibition of digestive enzymes, increased endogenous secretion in the gut and toxicity (Selle, personal communication). However, most sorghum cultivars used in the feed industry contain negligible levels of tannins.

The ME value of sorghum for poultry ranges from 15.2–16.5 MJ/kg DM (Black et al., 2005). Several factors affect the nutritive value of sorghum. The high degree of arabinose substitution in the cell walls of sorghum and the presence of significant amounts of uronic acid render them resistant to hydrolysis (Taylor, 2008). As a consequence, nutrient packaging may be more of a problem with sorghum than with other grains. The protein digestibility of sorghum is low and variable. This is associated with interactions between proteins and tannin and phytate and with the quality of endosperm proteins (Selle et al., 2009a). As for other cereals, the association between starch granules and the surrounding protein matrix affects the starch digestibility of sorghum. As with wheat, this is associated with endosperm texture, and soft cultivars are generally considered to have greater starch digestibility. Because of the association between grain hardness and particle size, fine grinding of hard cultivars may improve the digestion of sorghum starch, as was demonstrated for wheat (Péron et al., 2005). Cabrera (1994) showed that fine grinding of a hard sorghum cultivar resulted in better animal performance. Waniska et al. (1990) reported that starch digestion rates were lower for hard sorghum than soft sorghum.

Variation in the DE content of sorghum for pigs (15.8–17.4 MJ/kg DM; van Barneveld, 1999) is less than that for wheat and barley. Factors affecting the DE content of sorghum-based pig diets are likely to be similar to those for poultry diets (viz., insoluble NSPs, tannin, phytate and starch–protein interactions). For example, sorghum varieties with high tannin contents have lower DE contents (10–16%) than low tannin varieties (Kemm and Brand, 1996).

Rice (*Oryza sativa*) and rice by-products

Rice production is confined largely to Asia. Therefore, rice and its by-products (e.g., rice bran) are frequently used in animal diets in this region. Brown rice (rice from which the husk has not been removed) contains 8.5% CP, 9.1% crude fibre and 53.2% starch. Most of the fibre component is located in the husk. When the grain is de-hulled, rice crude fibre content is reduced to 0.8%. Because of its price, little rice is used in monogastric diets. However, rice by-products, especially rice bran, are very common feed ingredients. The bran fraction consists of the outer layers of the grain, some embryo and small amounts of endosperm. It contains up to 80% of the oil and 70% of the minerals and vitamins in the whole grain (Farrell and Hutton, 1990). Compared with cereal grains, full-fat and fat-extracted rice bran contain more crude protein (14.4% and 16.4%, respectively) and crude fibre (22.8% and 34.1%, respectively). The main NSP components of rice bran are arabinoxylans (mostly insoluble), which constitute up to 65% of the total NSP fraction. Rice bran also contains relatively high levels of phytate P (1.2–2.0%) and has low endogenous phytase activity (Selle et al., 2003).

Rice bran is generally considered a good source of high quality protein but its nutritional value varies widely because of differences in oil content and hull contamination. Limited information is available regarding the energy value of rice bran for pigs and poultry. The DE content of rice bran for pigs ranges from 10.2–13.9 MJ/kg DM, whereas the ME content of rice bran for broilers ranges from 9.4–12.8 MJ/kg DM (INRA, 2002). Farrell and Hutton (1990) reported greater variation in the DE content of rice bran for pigs (10.6–16.2 MJ/kg DM).

The use of exogenous enzymes in cereal-based diets

Fibre-degrading enzymes (or NSPases) hydrolyse soluble and insoluble NSPs in feed ingredients. Initially, NSPases were mainly added to viscous cereal-based diets to degrade soluble NSP polymers responsible for viscosity-related problems (viz., reduced performance and digestibility, bacterial proliferation in the gut and wet litter). The cell walls of cereal grains are mainly composed of cellulose and hemicelluloses in the form of arabinoxylans and β-glucans. Wheat and rye contain mostly arabinoxylans, whereas barley and oats contain a mixture of arabinoxylans and β-glucans (Choct, 2006). The cellulose and hemicellulose composition of cereal by-products is similar to that of the corresponding whole grains but NSPs are more concentrated than in the whole grains. Numerous studies have demonstrated the positive effects of NSPases and their mode of action (for reviews, see Bedford and Schulze, 1998 and Partridge, 2001). It is noteworthy that the magnitude of enzyme effects is less in pigs than in poultry because of their lower sensitivity to viscosity and greater bacterial fermentation in the distal part of the gut. Recently, interest has been expressed in the use of carbohydrases to degrade the insoluble cell-wall NSP fraction of non-viscous cereal-based diets, which is responsible for several anti-nutritive effects. Disruption of the endosperm cell-wall structure can reduce nutrient packaging problems. Starch and proteins become more accessible to digestive secretions, which enhances nutrient digestibility (Cowieson, 2005). Similar benefits of carbohydrases may also be expected with viscous cereal-based diets. For example, Amerah et al. (2009) showed that xylanase improved nutrient utilisation in broilers fed a diet containing hard wheat. Enzymatic breakdown of insoluble NSPs also reduces the water-holding capacity of fibre. A high water-holding capacity may result in entrapment of soluble nutrients, which would decrease their digestibility, and a reduction in feed intake. Inclusion of NSPases reduces these negative effects (Partridge, 2001). NSPases also decrease bacterial proliferation in the gut by limiting the amount of undigested nutrients available for the microflora (Bedford and Schulze, 1998; Dänicke et al., 1999).

The use of combinations of enzymes in monogastric diets is increasing. In general, these combinations are based on a xylanase backbone bound to enzymes such as an amylase and/or a protease. In addition to the positive effect that these enzymes have on digestion in young animals, the combination of amylase, protease and xylanase effectively degrades cereal endosperm and enhances nutrient digestion. This enzyme complex improves digestibility to a greater extent than a single NSPase because it disrupts cell walls and the starch–protein matrix (Cowieson, 2005; Partridge, 2001). This is especially relevant for cereals that have strong interactions between starch granules and the surrounding protein matrix (viz., cereals that are dried at a high temperature or grains with high hardness values). The ingestion of exogenous amylase and protease may also have a positive effect on the net energy content of the diet, as secretion of endogenous enzymes may be reduced, sparing energy.

Phytase supplementation is becoming increasingly common in the feed industry, not only because of environmental concerns, but also because of cost savings. The benefits of using phytase are twofold. Firstly, phytase has a direct benefit in that it improves P availability. This results in the inclusion of less inorganic P in the diet, which reduces feed costs and has environmental benefits. Secondly, phytase confers additional benefits through effects unrelated to P. These have been extensively reviewed by Selle and Ravindran (2007a, b). In summary, phytate is a potent anti-nutrient that negatively affects energy and protein digestibility by forming indigestible phytate–nutrient complexes and by increasing endogenous secretions in the gut. Finally, recent evidence suggests that a combination of phytase and NSPases elicits a greater response than phytase alone. By breaking down cell-walls, NSPases rapidly expose phytate molecules, which improves the efficacy of phytase in the digestive tract (Selle et al., personal communication).

Nutritional value of vegetable protein sources and by-products from the bio-ethanol industry in monogastric animal diets

The development of the biofuels industry has increased the demand for energy sources. As a consequence, dietary protein sources have become cheaper than dietary energy sources, and interest in the inclusion of grain legumes and DDGS in animal rations has increased.

Soybean meal

More soybean meal is produced than any other oilseed meal in the world. Inclusion of soybean meal in typical broiler or swine grower diets can satisfy up to 75% of amino acid requirements. Soybean meal contains almost no starch. Its CP content ranges from 40–50% and its total NSP content ranges from 20–25% (DM basis). The NSPs of soybean are mostly insoluble and the main sugar components (molar percent) are: galactose (28%), glucose (28%), arabinose (13%) and uronic acids (18%) (Ouhida et al., 2002). Compared with cereals, soybean meal contains more total P (0.64%) and the ratio of phytate P to total P is close to 65%, indicating that the availability of P in soybean meal is superior to that of maize, wheat or rice products (Selle et al., 2003; Tran and Skiba, 2005).

As for maize grain, the nutritional value of soybean meal for monogastric diets is believed to be very consistent. However, research has revealed that soybean meal quality is not as uniform or predictable as commonly thought (Irish and Balnave, 1993; Douglas and Parsons, 2000). The protein and energy content of soybean meal depends on the protein content of the soybeans from which the meal is derived, the amount of residual fat after processing and whether the hulls have been removed or not. The extraction process also affects amino acid digestibility because high temperatures damage proteins. On the other hand, high processing temperatures promote breakdown of anti-nutritional factors (ANFs) such as trypsin inhibitors.

Rapeseed/canola meal

Rapeseed meals produced in Asia and certain parts of Europe originally had high levels of glucosinolates, erucic acid and other anti-nutrients. New varieties developed in Canada in the 1970s have much lower levels of glucosinolates and erucic acid. These nutritionally superior varieties are known commercially as canola. Canola is now also grown in the USA, Europe and Australia. Rapeseed and canola meal have slightly lower CP and energy contents than soybean meal. The average CP content is 35%, but CP values range from 34–44%. Rapeseed and canola meals also have higher fibre, calcium and phosphorus contents than soybean meal. The total NSP content is about 29%, and arabinoxylan polymers are the main fibre components. Total P content ranges from 0.85–1.15% and the ratio of phytate P to total P is about 60–75% (Selle et al., 2003; Tran and Skiba, 2005). Finally, canola and rapeseed meal contain a high level of sulphur (1.1% vs 0.4% for soybean meal).

Because of the presence of arabinoxylans and several other ANFs in rapeseed meal, its inclusion in monogastric diets is limited. High dietary levels of rapeseed meal have been associated with palatability problems (especially in swine), reduced performance, metabolic disorders (liver and kidney problems) and leg abnormalities. In layer diets, high levels of rapeseed meal can impart a fishy taint to the yolk of eggs. This is because of the presence of a choline ester, sinapine, which results in the accumulation of trimethylamine in the yolk. All these problems, except for the effect of sinapine, are reduced when rapeseed meal is replaced by canola meal.

Legumes

Despite a good amino acid profile and high energy content, legumes contain several ANFs, which may reduce the nutritional value of these nutrients and result in high variation in protein quality (Gatel, 1994; Thorpe and Beal, 2001). The most important ANFs include NSPs, phytate, protease and amylase inhibitors, tannins, glucosides (e.g., vicine, convicine and saponins) and lectins. Legume NSPs are more complex in structure than those in cereals (Choct, 2006) and consist of a mixture of colloidal polysaccharides called pectic substances. These pectic substances are not present in cereal grains, or are only present in very small amounts. On the other hand, cellulose and xylan, the main NSPs in cereals, are only present in the hulls or husks of most legumes.

Lupins, peas and beans are among the most commonly used legumes in monogastric rations. The average CP content of peas, beans and lupins is 25.6%, 30.3% and 41.0%, respectively (Gatel, 1994). The average total NSP content of beans, peas and lupins is 16%, 20% and 38%, respectively. Legumes contain high levels of alpha-galactosides, a type of oligosaccharide that causes flatulence and reduces animal performance. Monogastric species do not synthesise the enzyme necessary to degrade these oligomers in the small intestine, but they can utilise the by-products of their fermentation by microbes in the hindgut or caecum (Kozlowska et al., 2001). In addition to protease inhibitors and lectins, peas, beans and lupins contain other anti-nutritional factors such as tannins (beans and peas), vicine and convicine (beans) and alkaloids (lupins). It is interesting to note that the level of protease inhibitors and lectins in raw peas and beans is much lower than that in raw soybean, suggesting that other factors are responsible for variation in the protein quality of peas (Gatel, 1994). Some researchers have suggested that accessibility problems associated with cell-wall structure could affect the digestibility of starch and proteins. This is supported by evidence of a positive effect of fine grinding or pelleting on the nutrient utilisation of peas (Carré et al., 1991).

DDGS a by-product of the bio-ethanol industry

Because of the removal of starch during the fermentation process, nutrients in DDGS are more concentrated than those in cereal grain. Nutrient levels in DDGS are three to four times higher than those in the corresponding grain. Maize DDGS contains 28.5% CP, 10.5% fat, 7.3% crude fibre and 0.68% total P; the remainder consists of residual starch and sugars, other fibre components (e.g., hemicellulose) and minerals. Wheat DDGS contains more CP (33.0%), less fat (5.4%) and more total P (1.05%) than maize DDGS. The fibre content is similar for both types of DDGS (7.1%). As for their respective cereal grains, the main NSP components of wheat and maize DDGS are arabinoxylans. However, there are more soluble pentosans in wheat DDGS than in maize DDGS. Maize and wheat DDGS contain a relatively high amount of available P. Because of the harsh process that grain undergoes during ethanol production, part of the phytate, IP6, which constitutes 90% of the phytate esters in cereal grains, is degraded to lower phytate esters (Widyaratne and Zijlstra, 2007). New types of DDGS have begun to appear on the market because some plants are producing ethanol from mixtures of grains such as maize and wheat or wheat and barley. This practice has been adopted to reduce reliance on a single grain source.

The nutritional quality of DDGS varies considerably from batch to batch within processing plants and between processing plants. A review of the scientific literature available to date showed that the coefficients of variation for the protein, lysine and total P contents of DDGS are 6.2%, 15.5% and 10.4%, respectively. Even higher coefficients of variation were observed for minerals such as sodium and calcium. Cozannet et al. (2009a) analysed 10 wheat DDGS samples and showed that the apparent ME content for poultry ranged from 8.40–11.62 MJ/kg DM. Noll (2006) showed that the ME content of maize DDGS for poultry ranged from 10.38–12.05 MJ/kg. Pedersen et al. (2007) analysed 10 maize DDGS samples and showed that the DE content for pigs ranged from 14.42–16.55 MJ/kg (as fed basis). Similarly, the DE values of 10 wheat DDGS samples analysed by Cozannet et al. (2009b) varied from 11.82 –16.22 MJ/kg DM. The low DE content of wheat DDGS, and its high variation, may be explained by the presence of high amounts of arabinoxylans (Zijlstra and Beltranena, 2008), especially the soluble fraction (Dalsgaard et al., 2008). Furthermore, some data suggest that lysine damage during processing is greater in wheat DDGS than in maize DDGS, which results in lower protein quality and amino acid availability for wheat compared with maize (Zijlstra and Beltranena, 2008).

The use of exogenous enzymes in diets containing significant amounts of vegetable protein sources or DDGS

Supplementation of broilers fed soybean meal based diets with a combination of xylanase, amylase and protease resulted in higher ileal digestible energy (IDE) (Douglas and Parsons, 2000). It also lowered variation in IDE among soybean samples. The positive effect of the enzyme blend was more pronounced with soybean meal samples that contained low levels of digestible energy (Douglas and Parsons, 2000). Guenter et al. (1995) investigated the benefits of various single enzymes on the nutritive value of canola meal. They observed positive effects for protease and carbohydrase when semi-purified canola meal diets were fed to broilers. They also showed that P release was greater in the presence of phytase in vitro. One of the benefits of protease may be associated with the hydrolysis of residual protease inhibitors and lectins in protein meals.

Several studies have demonstrated that exogenous enzymes have positive effects on the nutritional value of legumes. In a trial in which 10 common legumes were fed to three-week-old broilers using the precision feeding method (Sibbald, 1986), the addition of xylanase increased the true metabolisable energy value of most legumes (Wiryawan et al., 1995). A subsequent study by the same group using the same 10 legumes revealed that a combination of xylanase, amylase and protease improved the net protein ratio of the legumes (Wiryawan et al., 1997). Because of their complex structures, total depolymerisation of legume grains NSPs would require an extremely complex enzyme (Choct, 2006). In addition to the xylanase, amylase and protease combination, other types of enzymes such as mannanase and alpha-glucosidase are sometimes used when local ingredients such as palm kernel, linseed or copra meal are included in the diet.

Recent research with DDGS-containing diets has demonstrated the benefits of using enzyme blends. A combination of xylanase, amylase, protease and phytase improves performance, bone strength and digestibility in broilers (Péron et al., 2008; Ledoux et al., 2009). Similarly, a combination of xylanase and phytase improves nutrient and energy digestibility in pigs (Péron and Plumstead, 2008).

Conclusion

Worldwide, new economic and regulatory constraints have resulted in an increase in the complexity of diets fed to monogastric animals. However, developments in enzyme technology are helping the feed industry to overcome these challenges. Carbohydrases and phytases are the main enzymes used in diets at present, but there is a growing interest in the use of proteases. The primary function of feed enzymes is to improve nutrient digestibility, which lowers feed costs and reduces the output of excreta. Enzymes also reduce variation in nutritive value within feedstuffs and in animal responses. Because enzymes are substrate-specific, a good understanding of the composition of diet ingredients and variation in their quality is the key to maximising their efficacy (Dänicke et al., 1999). In the near future, greater research emphasis is likely to be placed on combinations of enzymes because of the increasing diversity of substrates.

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