The nutritional quality of feed ingredients

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The nutritional quality of feed ingredients is determined by the quantity and digestibility of amino acids (AA), lipids, carbohydrates, and minerals in the ingredients. The combined quantities of digestible AA, lipids, and carbohydrates also provide the total quantities of digestible energy (DE) in the diet.

AMINO ACIDS

The digestibility of AA is most correctly determined as standardized ileal digestibility (SID) of AA (Stein et al., 2007; NRC, 2012). To determine values for SID of AA, values for apparent ileal digestibility (AID) of AA are first determined, and these values are then corrected for the basal endogenous losses of AA (Stein et al., 2007).

To obtain values for AID, pigs that have a cannula installed in the distal ileum are usually used. Procedures for cannulating baby pigs, growing-finishing pigs, or gestating sows have been published (Gargallo and Zimmerman, 1980; Walker et al., 1986; Stein et al., 1998). Most diets are fed to the pigs for 7 days with the initial 5 days being an adaptation period and ileal digesta are collected for 8 hours per day during the last 2 days. This procedure has been used in multiple experiments and provides little trial to trial variation in the values that are calculated for AID (Knabe et al., 1989). The procedure to insert cannulas in the distal ileum is straight forward and easily tolerated by pigs. The main advantage of using this procedure is that several diets can be fed to the same pig during consecutive feeding periods. An alternative way of obtaining ileal digesta is to terminate the pigs at the end of the experiment and then collect digesta directly from the distal 30 to 40 cm of the ileum. This procedure has been used in some experiments (Moughan and Smith, 1987; Donkoh et al., 1994), but has the disadvantage that only one sample can be obtained per animal. Regardless of the procedure used to collect digesta, only a portion of the digesta can be collected and it is, therefore, necessary to include a marker in the diet. Chromium oxide and titanium dioxide are the most commonly used markers.

Values for AID of AA are determined by feeding diets containing the test ingredient and non-protein containing ingredients such as corn starch, oil, and sucrose. The determined AID of AA in the diet represents the AID of the AA in the test ingredient because the test ingredient provides all AA to the diet. This procedure is, therefore, called the "direct procedure" and has been used to determine AID of AA in multiple published experiments (Stein et al., 2006; Petersen et al., 2005; Baker and Stein, 2009; Kim et al., 2009). However, in some experiments, it is not possible to use the direct procedure because pigs do not tolerate, or are not willing to eat diets that contain large quantities of a specific ingredient. In that case, a basal diet containing a control protein-containing ingredient that is easily accepted by the pigs is formulated, and an additional diet in which the test ingredient is mixed with the control ingredient is also formulated. The AID of AA in both diets is then calculated using the direct procedure and the AID of the AA in the basal diet also represent the AID of AA in the control ingredient as explained above. The contribution of the control ingredient to the AA in the diet containing both the control ingredient and the test ingredient is then calculated and the AID of the AA in the test ingredient is calculated by difference. This procedure is, therefore, called the "difference procedure" and has been used to determine the AID of AA in high fiber ingredients and also in animal proteins (Mateo and Stein, 2007).

Basal endogenous losses of AA are determined by feeding a protein-free diet to the pigs, by feeding a low-

casein diet to the pigs, or by using the so-called peptide alimentation procedure, in which a diet containing hydrolyzed casein is fed to the pigs (Moughan, 2003). The protein-free procedure works well and is the most commonly used procedure in most parts of the world to determine basal endogenous losses of AA.

By correcting values for AID of AA for the basal endogenous losses of AA, values for the SID of AA are calculated. Values for SID of AA in different feed ingredients are additive in mixed diets, which is not always the case for values for AID of AA (Stein et al., 2005). Values for SID of AA should, therefore, always be used in formulation of mixed diets. Equations used to calculate values for AID, basal endogenous losses, and SID of AA have been published (Stein et al., 2007; NRC, 2012).

If the feed intake of pigs is less than 3 times the estimated energy intake for maintenance, values for AID and SID of AA will be incorrect (Moter and Stein, 2004), but values obtained from pigs fed 3 times the maintenance energy requirement are also representative of values obtained from pigs that have free access to feed (Chastanet et al., 2007). Pigs used in experiments to determine AID and SID of AA should, therefore, be fed at a level equivalent to at least 3 times the maintenance energy intake. The amount of feed allowed per pig per day can be fed in one meal or in 2 meals without affecting the AID of AA (Chastanet et al., 2007).

Amino acid concentrations in feed ingredients can be used to determine the so-called protein quality, which is calculated by expressing the concentration of each AA as a percentage of the concentration of crude protein (CP) in the diet. The greater the percentage of AA in the CP is the better is the protein quality. The concentration of digestible AA in the ingredient is calculated by multiplying the concentration of AA in the ingredient by the SID value for that AA.

A particular concern about protein quality relates to the fact that AA may be damaged if an ingredient or diet is heat treated because of the Maillard reaction (Nursten, 2005; Pahm et al., 2008). Because most commonly used feed ingredients go through some form of heat treatment during processing, most ingredients can potentially contain AA that are heat damaged. The AA that is most susceptible to heat damage is Lysine, but other AA can be affected as well (Gonzalez-Vega et al., 2011; Kim et al., 2012a). Heat damage will result in a reduction in the concentration of Lysine in the ingredient and also in a reduction in the SID of Lysine (Gonzalez-Vega et al., 2011). It is, therefore, possible to estimate the amount of heat damage in a feed ingredient by calculating the Lysine:CP ratio on a percentage basis and compare to the ratio in a non-heat damaged ingredient. If the ratio obtained for a specific ingredient is less than in the standard for the unheated ingredient then it can be assumed that the feed ingredient is heat damaged. It is also possible to estimate the degree of heat damage in a feed ingredient by calculating the amount of "reactive" Lysine in the ingredient. Reactive Lysine is assumed to represent the amount of Lysine that can be used for protein synthesis by the pig. Several procedures including the homoarginine procedure (Fontaine et al., 2007; Rutherfurd and Moughan, 2007); the Fluorodinitrobenzene method (Rutherfurd and Gilani, 2009), and the furosine procedure (Pahm et al., 2008; Cozannet et al., 2010; Gonzalez-Vega et al., 2011) can be used to calculate concentrations of reactive Lysine in a diet or feed ingredient. However, at this point, there is no evidence that calculation of reactive Lysine predicts the quality of the Lysine in a feed ingredient better than calculation of the Lysine:CP ratio (Kim et al., 2012a).

LIPIDS

Most of the lipids in feed ingredients are present in the form of triglycerides, but the concentrations of fatty acids in the triglycerides differ among ingredients, with many animal products containing more saturated fatty acids than most plant ingredients. However, there are exceptions to this rule as fish meal contains mainly long chained unsaturated fatty acids, and copra and palm kernel products contain mainly medium chained saturated fatty acids (NRC, 2012).

The concentration of fat in ingredients varies considerably with the least values (< 3%) observed for field peas, cereal grains, and solvent extracted oilseed meals. Many animal proteins (meat and bone meal, fish meal, feather meal, poultry by product meal, etc.) contain between 10 and 15% fat, although some ingredients of animal origin contain very little fat (blood products and most milk products). Most oilseed expellers contain between 5 and 15% fat, and some co-products from cereal grains such as distillers dried grains with solubles, rice bran, and bakery meal also contain between 5 and 15% fat. On the other hand, other co-products from cereal grains such as corn germ meal, hominy feed, corn gluten feed, and wheat middlings contain less than 5% fat.

Lipids may also be added to diets by including pure sources of fat directly in the diets. The energy value of added fats is directly proportional to the concentration of fatty acids in the fat (Powles et al., 1995), and in good quality sources of fat, the concentration of fatty acids is at least 85% and sometimes up to 92%. Because fats mainly consist of triglycerides, the concentration of free fatty acids is low in good quality fats. In intact fats from feed ingredients, less than 5% of the fatty acids are not bound to glycerol, but in pure sources of fats, some hydrolization of triglycerides has often taken place, and the concentration of fatty acids, therefore, may be greater. However, the concentration of free fatty acids should never exceed 15%. The combined sum of moisture, impurities, and un-saponifiable material should also be less than 3%.

Because the energy value of fat is greater than that of other nutrients (Ewan, 2001; NRC, 2012), the concentration of fat in a feed ingredient often can be used to predict the concentration of digestible energy in the ingredient, - although that is not always the case. The main contribution of dietary fat, therefore, is to increase the concentration of energy in the diet.

As is the case for AA, lipids are absorbed only in the small intestine and there is a substantial synthesis of fat in the large intestine, which results in reduced values for digestibility if values are determined over the entire intestinal tract compared with values determined at the end of the small intestine (Kil et al., 2010). Lipid digestibility should, therefore, be determined as ileal digestibility values and to avoid the negative influence of endogenous fat secreted into the small intestine, values for the true digestibility of fat should be determined when feed ingredients are evaluated (NRC, 2012). There is, however, relatively great variability among feed ingredients in the digestibility of fat and the digestibility of fat in some ingredients is less than 50% (Noblet et al., 1994). It is also recognized that intact sources of fat are less digestible than fat that has been extracted from the ingredient and then are added back to the diet (Adams and Jensen, 1984; Kil et al., 2010).

Oxidation of fats will render them rancid, which will reduce the energy value and the palatability of the fat. Peroxide values are sometimes determined as an indicator of oxidation, but because peroxide values are elevated only during the early stages of oxidation, this is not always an accurate estimate of fat quality (Ross and Smith, 2006). A low value for peroxides may indicate no oxidation or advanced oxidation where peroxide values have been converted to secondary oxidation products (NRC, 2012). Determination of values for TBARS, benzene, or anisidine are also commonly used to determine the degree of oxidation in fats, but none of these measurements are completely accurate in determining the degree of fat oxidation (NRC, 2012). To prevent oxidation in fats, antioxidants should be added to high-fat ingredients and to mixed diets.

CARBOHYDRATES

Carbohydrates are divided into starch and sugars, and non-starch polysaccharides (NSP). The concentration of starch and sugars is greatest in cereal grains and least in most oilseeds and oilseed meals. Some of the co-products from cereal grains such as distillers dried grains with solubles and corn gluten meal also have low concentrations of starch and sugars. The concentration of NSP also varies greatly among feed ingredients with the least values for cereal grains and the greatest concentrations in many co-products (corn gluten feed, distillers dried grains with solubles, soybean hulls, corn germ meal, etc.). Among the oilseed meals, the least concentrations are in soybean meal, and the greatest concentrations in palm kernel meal, copra meal, and sunflower meal. The concentration of carbohydrates is close to zero in all ingredients of animal origin except for milk products where the concentration of lactose may be between 40 and 90%.

Starch and sugars are usually well digested by pigs, and results in absorption of glucose in the small intestine, and the majority (> 90%) of the sugars and starch in feed ingredients is usually digested in the small intestine with a subsequent absorption of glucose and other monosaccharides before the end of the small intestine. In contrast, the NSP cannot be digested and the only way an animal can utilize the energy in the NSP is if they are fermented by intestinal microbes, which primarily, but not exclusively, takes place in the large intestine. The fermentability of NSP varies between 40 and 90% (Back Knudsen, 2011) with the greatest values observed for soluble NSP, and the least values for the insoluble NSP (Urriola et al., 2010). Because fermentation mainly takes place in the large intestine, values for the total tract disappearance, rather than values for ileal disappearance, should be determined to evaluate the NSP fraction in an ingredient. Unlike what is happening for AA and lipids, there is no secretion of endogenous carbohydrates into the digestive tract and values for apparent total tract disappearance are, therefore, not influenced by endogenous losses. As a consequence,

there is no need to calculate standardized or true values for the digestibility of carbohydrates and therefore, values for AID can be used for starch and sugars and values for apparent total tract digestibility (ATTD) can be used for NSP (NRC, 2012).

Whereas digestion of sugars and starch results in absorption of glucose and other monosaccharides, fermentation of NSP results in absorption of short chained fatty acids that may be utilized by the pig for synthesis of ATP, synthesis of glucose, or for synthesis of fatty acids. However, because fermentation is an energy requiring process, the energy contribution of NSP is much less than of starch and sugars (Just et al., 1983; Shi and Noblet, 1994; Black, 1995). As a consequence, the energy value of a feed ingredient is usually negatively correlated with the concentration of fiber in the ingredient. However, because of the increased costs of using cereal grains and soybean meal in diets, more co-products and alternative ingredients are being used and most of these ingredients contain more NSP and less ME than cereal grains and soybean meal. As a consequence, diets containing co-products often contain less energy than diets based on cereal grains and soybean meal.

ASH AND MINERALS

Ash does not contribute to the energy value of feed ingredients, but the minerals that a feed ingredient contains are included in this fraction. Because of the lack of energy in the ash fraction, the energy concentration in a feed ingredient is usually negatively correlated with the amount of ash in the ingredient (Noblet et al., 1994; Pedersen et al., 2007; Olukosi and Adeola, 2009). The concentration of ash in cereal grains and most intact ingredients of plant origin is usually less than 3%, but many co-products may contain between 5 and 10% ash. Greater concentrations of ash than these levels often indicate contamination with sand or dirt, which can be a problem for many ingredients if harvesting conditions are not ideal. High concentrations of ash may also be observed in ingredients produced from potatoes and cassava if the roots of these plants are not completely cleaned before usage.

Many ingredients of animal origin have greater concentrations of ash than ingredients produced from plants. This is true in particular for ingredients that contain the bones of animals, such as poultry by product meal, meat and bone meal, fish meal, etc. Increased concentrations of ash in these ingredients usually indicate increased concentrations of bones in the ingredient. Specifically for fish meal, the concentration of ash may vary from approximately 10% if the meal is produced from whole fish to more than 25% if large quantities of fish bones form the fish filet industry are included in the meal. Because of the reduced energy that is associated with increased concentrations of ash, the value of fish meals with greater concentrations of ash is less than of meals with lower concentrations of ash. Poultry by product meal consists of whole spent hens as well as offal from the chicken food industry, which often contains bones. A greater concentration of ash in poultry by product meal, therefore, indicates a greater concentration of offal in the meal and a reduced nutritional value.

Blood products usually contain between 5 and 8% ash and milk products may contain between 2 and 15% ash dependent on the processing the product has gone through. The relationship between ash concentration and ME in whey permeate was recently illustrated by Kim et al. (2012b), who reported ME values of 3,009 and 3537 kcal/kg for whey permeate containing 15.8 and 1.7% ash, respectively.

The ash fraction also contains the minerals in feed ingredients and of all the minerals that are needed by animals, phosphorus has the greatest economic value because this mineral is needed in relatively large quantities, and it is expensive to buy. The digestibility of phosphorus is most accurately reported as the standardized total tract digestibility (STTD) because values for the ATTD of P not always are additive in mixed diets (Stein, 2011). As a consequence, the basal endogenous losses of phosphorus need to be determined, but results of multiple experiments have demonstrated that basal endogenous losses do not vary much among experiments and a common value of 190 or 200 mg per kg dry matter intake may be used (Stein, 2011; NRC, 2012). It is, therefore, not necessary to determine basal endogenous losses in each experiment aimed at determining phosphorus digestibility. Instead, values for ATTD can be corrected for basal endogenous losses using the constant value of 200 mg/kg dry matter intake and values for STTD can then be calculated. Because it is possible to collect all feces, it is not necessary to include a marker in the diet to determine values for ATTD and STTD of phosphorus. Equations for calculation of ATTD and STTD have been published previously (Almeida and Stein, 2010; NRC, 2012). The digestibility of calcium is not reported as often as the digestibility of phosphorus, but recent unpublished work from the University of Illinois indicates that values for the STTD of

calcium also need to be calculated to accurately predict calcium digestibility in a mixed diet.

Most plants store most of the phosphorus by attaching it to an inositol ring to form phytate and most phytate bound phosphorus has a low digestibility when fed to pigs and poultry (Eeckhout and de Paepe, 1994). However, the digestibility of phosphorus in plant ingredients may be improved by addition of microbial phytase to the diets (Jongbloed et al., 1992; Cromwell et al., 1995). It has also been demonstrated that feed ingredients that have been fermented or soaked in water have greater digestibility of phosphorus than other plant based feed ingredients because fermentation and soaking hydrolyzes the bonds connecting phosphorus to the inositol ring in phytate (Almeida and Stein, 2012; Rojas and Stein, 2012a).

The digestibility of phosphorus in feed ingredients of animal origin usually is much greater than in plant based feed ingredients because animals do not store phosphorus in the form of phytate. As a consequence, the digestibility of phosphorus in milk products and blood products are greater than 90% (Almeida and Stein, 2011; Kim et al., 2012b). However, the digestibility of phosphorus in bone ash is less than the digestibility of phosphorus in soft tissue (Jongbloed and Kemme, 1990), and feed ingredients that contain bone, therefore, have a reduced digestibility of P compared with milk and blood products. As a consequence, the digestibility of P in meat and bone meal, fish meal, and poultry by product meal is usually between 60 and 70% (Rojas and Stein, 2012b).

Cereal grains contain very little calcium, but the oilseed meals, canola meal in particular, contain greater quantities of calcium. Feed ingredients of animal origin that contain bone also contain calcium because calcium and phosphorus are deposited in bone in a 2:1 ratio (Crenshaw, 2001). The digestibility of calcium in feed ingredients has been reported only for a few ingredients, and in most cases, values between 50 and 70% have been reported (Bohlke et al., 2005).

ENERGY

The energy concentration in a feed ingredient is determined as gross energy (GE), which is determined by adiabatic bomb calorimetry. Values for DE and metabolizable energy (ME) are determined by subtracting the energy excreted in feces and urine, respectively, from GE. To determine fecal and urine energy, pigs are placed in metabolism cages and feces and urine are collected quantitatively. For accurate collection of feces, a start and a stop marker should be used to determine initiation and conclusion of collection (Adeola, 2001; NRC, 2012). To determine net energy (NE), the heat increment needs to be determined and this requires use of indirect calorimetry and is not often done for practical feed ingredient evaluation. Instead, values for NE are usually calculated from previously developed prediction equations (Sauvant et al., 2004; NRC, 2012). As an alternative to using indirect calorimetry, the comparative slaughter procedure may also be used to determine NE values in feed ingredients and diets (Ewan, 2001).

Fat contains more energy than protein and carbohydrates (Ewan, 2001), and the greater the concentration of fat in a feed ingredient is, the greater is the concentration of ME or NE usually in that ingredient. However, high concentrations of crude protein also will result in high values for ME as has been shown for high protein distillers dried grains with solubles (Widmer et al., 2007). In most cases, a high concentration of starch in the ingredient also indicates a high energy value. This is not so much because starch has a high energy value, but a high starch concentration usually indicates a low concentration of NSP, and because NSP have the least concentration of ME of all the energy contributing ingredients, a low concentration of this fraction has a positive impact on the ME in the ingredient. In contrast, feed ingredients that have a high concentration of NSP usually have a low concentration of ME and NE. The same is the case for ash as explained above and feed ingredients that have a high concentration of NSP and/or ash, usually have a low concentration of ME and NE. Most co-products have high concentrations of NSP and low ME concentrations, whereas most cereal grains have low concentration of NSP and therefore, relatively high concentrations of ME and NE. A few co-products such as some of the corn co-products contain high levels of NSP and high concentrations of fat and these ingredients, therefore, may have values for ME that are similar to values in cereal grains (Pedersen et al., 2007). Likewise, many of the animal proteins have high concentrations of fat and also high concentrations of ash, which result in medium or low concentrations of ME in these ingredients.

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