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Nutritional Properties and Feeding Values of Soybeans and Their Coproducts

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Introduction

Soybean meal (SBM) is the number-one protein source used in the poultry and livestock industries throughout the world. Of all the SBM that is sold in the United States, >50% is used in diets fed to poultry, and 26% is used in diets fed to swine. Ruminant animals, dogs, cats, and others account for the remaining portion of this usage (Fig. 18.1).

The main reason for the popularity of SBM is the unique composition of amino acids (AAs) that complements the AA compositions of many cereal grains. The excellent AA quality in SBM is also the reason why SBM is now increasingly being used in the pet-food industry. While SBM is by far the most popular soybean product in livestock diets, other products are also being used to a varying degree. These products include full-fat soybeans, soy protein concentrate (SPC), soy protein isolate (SPI) soy-

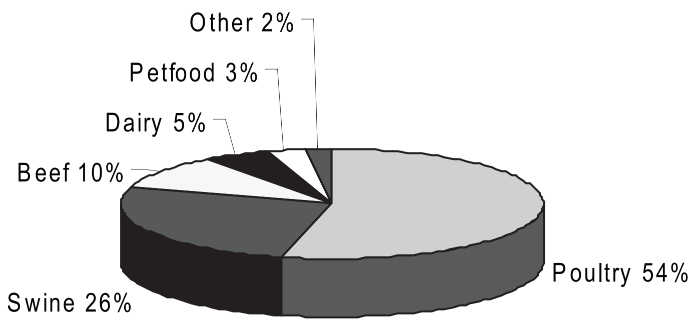

Fig. 18.1. Use of soybean meal in the United States by livestock, poultry, and companion animals.

bean oil, and soybean hulls. Each of these products have unique nutritional properties that make them appropriate for inclusion in diets fed to certain categories of animals. The objective of this chapter is to summarize current knowledge about the nutritional value of soybean products fed to poultry, livestock, and companion animals.

Soybean Products in Diets Fed to Poultry

SBM is an extensively used ingredient in poultry diets and is the largest source of protein in poultry diets in much of the world. Dehulled solvent-extracted meal is the most widely used SBM product because of its large production and higher protein and energy content than lower protein meals that contain hulls. Poultry derive very little, if any, energy from soybean hulls. SBM has advantages over most other oilseed meals with respect to digestible energy and protein/AA (Table 18.1). This is important because providing adequate quantities of energy and protein or AA accounts for >90% of the feed costs in most poultry diets. The concentration of metabolizable energy (ME) in SBM is 11 to 25% greater than that of other commonly used oilseed meals. This difference is largely due to the lower fiber concentration of SBM compared with most other meals. The digestibilities of AAs in SBM are generally greater than in other oilseed meals. This difference is usually greatest for lysine.

Poultry are by far the largest consumers of SBM in the United States. Poultry diets in the United States and much of the world are composed primarily of grain and SBM. Corn and sorghum are the two most common grain sources used in the United

Table 18.1. Metabolizable Energy and Protein Concentration and True Digestibilities of Amino Acids in Soybean Meal and Other Oilseeds Fed to Poultry[a]

Item	Dehulled soybean meal	Canola meal	De-hulled sunflower meal	Cottonseed meal[b]	Peanut meal[c]
Energy, ME_n, kcal/kg	2,711	2,150	2,495	2,041	2,391
Protein, %	53.9	40.9	48.8	49.1	55.1
Digestibility of AA, %					
Arginine	92	90	93	87	84
Cysteine	82	75	78	73	78
Lysine	91	80	84	67	83
Methionine	92	90	93	73	88
Threonine	88	78	85	71	82
Valine	91	82	86	78	88

[a] Values for metabolizable energy (ME_n) and protein are on a dry matter basis. All values are from NRC (1994).
[b] Prepressed solvent-extracted, 44% protein.
[c] Solvent-extracted.

States. Corn or sorghum and SBM complement one another very well in meeting the protein and AA requirements of poultry. For example, the grains generally contain low concentrations of protein, lysine, and tryptophan, whereas SBM contains high concentrations of these nutrients. For many years, the main limiting factor for SBM use in poultry feeds was its deficiency in the sulfur AAs (methionine and cysteine). However, the commercial availability of inexpensive feed-grade sources of methionine resulted in the routine addition of this AA to grain-SBM diets. Also, for many years people believed that grain-SBM diets were deficient in certain "unidentified growth factors" and that ingredients, such as fish meal, were needed to obtain maximal growth performance. Subsequent research showed that most of the unexplained growth response often obtained from these ingredients, such as fish meal, was due to nutrients such as vitamin B_{12} and selenium. Consequently, the routine supplementation of poultry feeds with these and other nutrients today enables producers to obtain optimal performance using grain–SBM diets.

Soybean Products as Protein Sources for Poultry

Protein Quality of Soybean Products

The protein quality of SBM was reviewed by Baker (2000). The protein quality of SBM is high for poultry, and SBM is a particularly good source of both lysine and tryptophan. SBM is also an especially good source of lysine. When the digestible lysine concentration in SBM is compared to the required amount of lysine for chicks (per unit of protein), the amount of digestible lysine in SBM actually exceeds the requirement (Baker, 2000). No other oilseed comes close to being as good a source of lysine as SBM for poultry. SBM, however, is not a perfect protein source. When compared to the ideal AA contents needed by poultry, the protein in SBM is deficient in methionine plus cysteine, threonine, and valine. Consequently, virtually all poultry diets that contain large amounts of SBM are supplemented with a source of methionine (e.g., DL<small cap DL>-methionine or the hydroxy analog of methionine). Soybean protein and SBM–grain combinations contain excesses of some AAs, particularly leucine, but these excesses are generally less than those for other oilseed meals and other oilseed–grain combinations. SBM is also a good source of arginine, which is beneficial for poultry because they cannot synthesize arginine, and thus, have much higher requirements for this AA than mammals.

When examining the protein quality of other soy products, such as SPC (approximately 64% protein) and SPI (approximately 85% protein), compared with SBM, both similarities and differences are found. SPC and SPI are first-limiting in methionine + cysteine and second-limiting in threonine, the same as for SBM. The overall protein quality of SPI, however, is lower than that of SBM (Emmert & Baker, 1995), which is due to the lower concentrations of total and digestible methionine + cysteine and threonine in the protein of the SPI than in the protein of SBM or SPC (Emmert

& Baker, 1995). The latter study also showed that the true digestibilities of AAs in SBM, SPC, and SPI were similar. More recent work by Batal and Parsons (2003), however, indicated that the apparent digestibilities of AAs in SPC and in SPI fed to chicks are greater than in SBM. When chicks were fed dextrose-based diets containing the various soy products, true digestibility of AAs increased with increasing age from 3 or 4 days to 21 days of age, and true digestibility coefficients for AAs were generally greater for SPC and SPI than for SBM.

Soybean Products as Protein Sources in Feeds for Broiler Chickens and Turkeys

This subject was reviewed for broiler chickens by Penz and Brugali (2000). The primary type of SBM used in broiler chicken diets is dehulled, solvent-extracted SBM, which contains ~48% protein. The lower protein SBM with the hulls, containing 44–45% protein, can also be used; however, growth performance, particularly feed efficiency, will be better for chicks fed dehulled SBM (Penz & Brugali, 2000). Full-fat soybeans, either toasted or extruded, are also an excellent protein source for broilers. The inclusion rates of full-fat soybeans may depend on the physical form in which they are fed. When high amounts of full-fat soybeans are fed, the diets may need to be pelleted to improve diet density or breakdown of plant cells to better release nutrients (Waldroup & Cotton, 1974); these latter researchers concluded that most diets should not contain >25% of full-fat soybeans. It is possible that greater concentrations may be used in pelleted diets; however, other studies indicated that full-fat soybeans can replace up to 100% of the SBM in broiler diets (Penz & Brugali, 2000). The principles for using SBM in turkey diets are similar to those for broiler chickens, but SBM is often used at higher concentrations in diets fed to young turkeys due to their higher AA requirement compared with broiler chickens.

Soybean Products as Protein Sources in Feed for Laying Hens

The above discussion for broilers and turkeys also applies to laying hens. Dehulled SBM is generally preferred over SBM with hulls due to its higher protein and metabolizable energy concentration. As reviewed by Penz and Brugali (2000), full-fat soybeans are an excellent ingredient for laying-hen diets if the soybeans are heated properly. Studies with laying hens reported adverse effects of feeding high levels of toasted or extruded soybeans; however, these results may be explained by the under-heating of the soybeans. Thus, the effective utilization of full-fat soybeans in laying-hen diets depends greatly on the proper processing of the soybeans.

Assessment of Protein Quality of Soybean Products

Parsons (2000) reviewed this topic. Variation in protein quality among soybean products is due to the protein and AA concentrations of the product and the bioavailability of the AAs in the product. Variation in AA bioavailability among soybean products is primarily due to either insufficient or excessive heat processing. Several antinutritional factors (e.g., protease inhibitors, lectins) must be inactivated, and heating is the primary means of accomplishing this. Several different animal assays can be used to estimate protein quality of soy products. The three most commonly used procedures are protein efficiency ratio (PER) assays, slope–ratio growth assays, and digestibility or balance assays. In the PER assay for poultry, soy products are fed as the only source of protein (~10% protein in the diet) for 10 to 14 days, and PER is calculated by dividing weight gain (g) by protein intake (g). This type of assay was used to evaluate several different soy products (Emmert & Baker, 1995). The PER value of SBM is greater than the PER of SPC and SPI, and the PER values vary among different isolates (Emmert & Baker, 1995). Thus, the PER assay was shown to be sensitive for detecting differences in protein quality among soy products. The PER assay, however, has limited usefulness from a practical standpoint because it provides no direct information on bioavailability or digestibility of specific AAs, and it is not sensitive in detecting the reduction in protein quality or lysine digestibility due to excessive heating.

Slope–ratio growth assays are usually considered the best standard assay for measuring bioavailability of AAs in soy products. These assays, however, have several disadvantages, such as expense and time, and dietary factors other than the limiting AAs can affect growth, which was illustrated for SBM by Baker (1978). Due largely to the disadvantages of the slope–ratio assays, digestibility or balance assays are used more extensively to estimate bioavailability of AAs. The two most common assays for poultry are the precision-fed cecectomized rooster assay (Parsons, 1985) and the ileal digestibility assay using the slaughter method (Angkanaporn et al., 1996). The cecectomized rooster assay is faster and less expensive, but the ileal assay has the advantage that no surgery on the animals is needed. Both of these assays were used to evaluate SBM and other soy products, and results indicate that true digestibility coefficients for AAs in high-quality soy products are usually 90% or greater. The primary factors that cause reduced AA digestibility are insufficient or excessive heating. The effects of insufficient heating are not the same as those for excessive heating. The digestibilities of all AAs are reduced by underheating, whereas only the digestibility of lysine, and to some extent cysteine, is reduced by overheating (Parsons, 2000).

In addition to the in vivo or animal assays, several in vitro assays can be used to estimate protein quality of soy products. Analyzing for crude protein and lysine and then calculating lysine as a percentage of the protein may be a useful indicator of overprocessing or excessive heating. In addition to the digestibility of lysine being reduced by excessive heating, the analyzable lysine level may also be reduced due to total destruction during the formation of advanced Maillard reaction products (Hurrell & Carpenter, 1981). Consequently, overheating may reduce the analyzed lysine to crude protein ratio. For example, high-quality SBM usually has a lysine-to-protein ratio of 6.2 to 6.6. If the ratio is <6.0, then the SBM may be heat-damaged (Parsons, 2000).

The in vitro assay that is used most extensively for SBM in the poultry industry is the urease assay (AOCS, 1973). It is widely used because it is simple and is a reasonably good indirect indicator of the level of active trypsin and chymotrypsin inhibitors and lectins in soy products. The general or optimal desired range in urease pH change for poultry is 0.05–0.20. The exact critical lower and upper limits for the urease index, however, are controversial (Waldroup et al., 1985). For example, commercial SBM often has a urease pH change value of <0.05. This low value only indicates that the SBM perhaps was overheated and does not mean that the SBM or soy product was indeed overheated. In fact, the primary weakness of the urease assay is that, although it is a good indicator of insufficient heating, it is not a good indicator of overheating. Consequently, the KOH protein solubility assay (Araba & Dale, 1990; Parsons et al., 1991) was evaluated and shown to be a reasonably good method for determining overheating of SBM. Araba and Dale (1990) concluded that the critical limit for KOH protein solubility was approximately 70% and that values below this level are indicative of overprocessing. Protein solubility in water (e.g., protein dispersibility index), dye binding, and colorimetric assays were also shown to be useful assays, but these are not used to a great extent commercially.

Soybean Products as Energy Sources for Poultry

Dale (2000) reviewed the topic of soybean products as energy sources for poultry. Although soybean products are primarily considered as protein sources for poultry, they also contribute a large amount of energy to poultry diets. In typical grain–SBM diets, SBM furnishes ~25% of the metabolizable energy (ME) in the diet. The primary weakness of SBM as an energy source is the very poor digestibility of the carbohydrate fraction. As calculated by Dale (2000), SBM contains approximately 10% more gross energy (GE) than corn, but SBM contains only about 72% of the ME of corn because of the poor digestibility of the carbohydrates in SBM. This low digestibility results in a large amount of energy being lost in the excreta, a large amount of dry matter being excreted as manure, and a dilution of energy and other nutrients in the diet.

Carbohydrates make up 32–35% of SBM. The carbohydrate fraction is composed mainly of nonstarch polysaccharides and oligosaccharides such as sucrose, raffinose, and stachyose. The reason for the extremely low digestibility of the soy carbohydrates is unknown and somewhat controversial. The oligosaccharides, raffinose and stachyose, are often cited as the main culprits, but disagreement exists as to the extent of their role. Removing the oligosaccharides by ethanol extraction was reported to greatly increase the ME of SBM (Coon et al., 1990). However, Irish et al. (1995) later reported that removing the oligosaccharides had little or no effect on the ME of SBM. Parsons et al. (2000) reported that removing the oligosaccharides by genetics or plant breeding increased the ME of SBM by 7–9%. Thus, although the raffinose and stachyose in SBM are contributors to its low energy content, the poor digestibility of the nonstarch polysaccharides may be the main reason for the low ME of SBM.

The most effective way to increase the energy values of SBM and other soybean products is to use different processing procedures. One processing modification is to remove less or none of the oil. Properly heated full-fat soybeans (18% oil) have ME values of 3,300–3,350 kcal/kg compared with 2,440 kcal/kg for SBM (Dale, 2006; NRC, 1994). Mechanically processing soybeans by extruding and expelling (screw pressing) to yield a SBM with 6–8% oil also results in more energy than what is present in solvent-extracted SBM (Zhang et al., 1993). Another alternative is to remove the carbohydrates during processing. For example, the MEs of SPC and SPI are considerably greater than in SBM (Batal & Parsons, 2003). Not one of these methods increases the digestibility of carbohydrates in SBM and other soy products. This is an area of great importance and potential in poultry nutrition. It also, however, seems to be a very challenging and difficult area. Plant breeding and the use of exogenous feed enzymes demonstrated limited or no commercial success.

Genetically Modified Soybean Products

During the last 15 to 20 years, considerable interest and activity arose in developing new genetically modified or genetically enhanced crops and feed ingredients that have an increased nutritional value. For soybeans, these genetically modified plants include those with modified input traits for insect protection and herbicide tolerance and those with modified output traits for increased nutritional value. The insect-protected and herbicide-tolerant traits primarily include inserting genes from *Bacillus thuringensis* (*Bt*) and for glyphosate tolerance (Roundup family of herbicides). Although these genetic modifications were very successful commercially, they result in no change in nutritional composition or value of the soybeans (Hammond et al., 1996; Kan & Hartnell, 2004). Soybeans with genetic modifications for output traits that increase the nutritional value of soybeans or SBM for poultry include reduced trypsin inhibitor soybeans and low-lectin soybeans (Batal & Parsons, 2003; Douglas et al., 1999; Han et al. 1991), low-oligosaccharide SBM (Parsons et al., 2000), and high-protein soybeans (Edwards et al., 2000). Soybeans with reduced concentrations of phytate and increased digestibility of phosphorus were also developed. All of these modifications result in a substantial increase in nutritional value for poultry, but not one of these modified soybeans or SBM was successfully commercialized. This lack of success was mainly due to agronomic problems with the nutritionally enhanced crops and also to a market infrastructure that is primarily commodity-based, making identity preservation and marketing of the modified soybeans and/or SBM difficult.

Soybean Products In Diets Fed To Swine

Soybean products are included in most diets fed to swine in the United States and in most countries in the world because soybean protein is recognized as the premier protein source for pigs (Shelton et al., 2001). Intact soybeans may be used in swine feeding, but SBM is by far the most common protein source used for all categories of pigs (Cromwell, 2000). Processed products, such as SPC or SPI, are sometimes used in diets fed to weanling pigs. Newer enzymatically treated or fermented soybean products, such as Hamlet protein and PepSoyGen, were recently introduced to the feed industry and are mainly used in diets fed to weanling pigs (Pahm & Stein, 2007b).
The majority of soybean products included in diets fed to pigs are used to increase the dietary concentrations of AAs. However, soybean oil may also be used in diets fed to weanling, growing, and finishing pigs as an important source of energy (Mahan, 1991; Owen et al., 1996). Soybean hulls that are produced by dehulling soybeans may also be included in diets fed to sows and growing-finishing pigs in quantities of up to 15% without negatively affecting performance (Kornegay, 1981). However, because of the high concentration of fiber in soybean hulls, the digestibilities of energy and most dietary nutrients, including AAs, are reduced if soybean hulls are included in the diets (Dilger et al., 2004; Kornegay, 1981). Therefore, soybean hulls are usually not used in diets fed to swine.

Nutrients and Energy in Soybean Products

Nutrient and Energy Concentrations in Soy Products

Although all soybean products except soybean oil are included in diets fed to swine to increase the concentration of AAs in the diets, soybean products also contribute energy and other nutrients. It is beyond the scope of this contribution to discuss nutrients other than AAs and P along with energy provided by soybean products, but it is recognized that soybean products also supply significant quantities of vitamins and many minerals to swine diets.

The concentrations of energy, AAs, and P in full-fat soybeans as well as in SBM, SPC, and SPI have been published (NRC, 1998; Table 18.2). The concentration of GE in soybean meal is relatively constant across sources of soybean meal collected at different locations (van Kempen et al., 2006). However, the processing procedure used to produce the SBM has an impact on the total amount of energy in the meal. Screw-pressed meals usually contain more energy than solvent-extracted meals because screw-pressed meals have a greater concentration of fat (Woodworth et al., 2001). Likewise, dehulled SBM contains more energy than nondehulled SBM because of the lower concentration of fiber (Woodworth et al., 2001).

Compared with most other protein sources, soy protein has a relatively high concentration of lysine and tryptophan. The concentrations of these two AAs are relatively low in most cereal grains, and particularly so in corn. Therefore, lysine is

Table 18.2. Concentration of Energy, P, and Amino Acids in Soybean Products Fed to Swine [a]

Item	Soybean meal		Full-fat soybeans	Soy protein concentrate	Soy protein isolate
	Nondehulled	Dehulled			
Energy, kcal DE/kg	3,490	3,685	4,140	4,100	4,150
Energy, kcal ME/kg	3,180	3,380	3,690	3,500	3,560
Crude protein, %	43.8	47.5	35.2	64.0	85.8
Phosphorus, %	0.65	0.69	0.59	0.81	0.65
Calcium, %	0.32	0.34	0.25	0.35	0.15
Amino acids, %					
Arginine	3.23	3.48	2.60	5.79	6.87
Histidine	1.17	1.28	0.96	1.80	2.25
Isoleucine	1.99	2.16	1.61	3.30	4.25
Leucine	3.42	3.66	2.75	5.30	6.64
Lysine	2.83	3.02	2.22	4.20	5.26
Methionine	0.61	0.67	0.53	0.90	1.01
Cysteine	0.70	0.74	0.55	1.00	1.19
Phenylalanine	2.18	2.39	1.83	3.40	4.34
Tyrosine	1.69	1.82	1.32	2.50	3.10
Threonine	1.73	1.85	1.41	2.80	3.17
Tryptophan	0.61	0.65	0.48	0.90	1.08
Valine	2.06	2.27	1.68	3.40	4.21

[a] All data are from NRC (1998).

the first limiting AA in grain-based diets fed to pigs, and tryptophan is the second, third, or fourth limiting AA in diets based on corn and fed to monogastric animals (Sharda et al., 1976). The AA profile of soybean protein, however, complements the AA profile of cereal grains because of the relatively high concentrations of lysine and tryptophan.

Variabilities in the nutrient compositions of different sources of soybeans exist. This is true not only of soybeans and SBM obtained from different countries, but also of samples obtained from different locations within the United States (Grieshop et al., 2003; Karr-Lilienthal et al., 2004). However, the mean concentrations of nutrients in 10 soybean samples and in 10 SBM samples obtained from different locations in the United States are in good agreement with the values published by NRC (Grieshop et al., 2003). Likewise, when samples of nondehulled and dehulled SBM from 16 different sources in the United States were analyzed for AA composition, mean values that are close to NRC values were obtained (Cromwell et al., 1999). Therefore, good agreement exists on the average nutrient composition in soybean products, but variability among sources may exist. Within the United States, concentrations of protein and AAs in soybean products are reduced for soybeans grown in the northern part of the country as compared with the central or southern states (Cromwell et al., 1999; Grieshop et al., 2003). In addition, newer varieties of soybeans that were specifically selected for greater concentrations of proteins are now available; SBM obtained from these beans have greater concentrations of protein and AAs than meals produced from conventional soybeans (Pahm & Stein, 2007a).

Amino Acid Digestibility of Soybean Proteins by Pigs

The apparent and standardized ileal digestibilities of AAs in SBM (with or without hulls) and in other soybean products have been measured in numerous experiments, and results were summarized (NRC, 1998; Table 18.3). The digestibilities of AAs in SBM collected from different geographical locations in the United States are relatively constant (van Kempen et al., 2002). All sources of soy protein need to be heated prior to feeding to inactivate antinutritional factors, mainly protease inhibitors and lectins, present in raw soybeans (Qin et al., 1996). However, the form of heat applied to soy protein may influence the digestibilities of AAs in the product (Opapeju et al., 2006; Woodworth et al., 2001), and several other factors were shown to influence the digestibilities of AAs in soy protein. In general, the more processed the soy protein is, the greater are the digestibilities of AAs. Therefore, AAs in SPI and SPC are usually more digestible than AAs in SBM (Pahm & Stein, 2007b), and AAs in dehulled SBM have a greater digestibilities than AAs in nondehulled SBM (NRC, 1998). The latter observation is consistent with reports showing that soybean hulls reduce the digestibilities of AA in SBM (Dilger et al., 2004). Also, likely the reason for the increased

Table 18.3. Standardized Ileal Digestibilities of Amino Acids (%) in Soybean Products Fed to Swine [a]

Amino acid	Soybean meal		Full-fat soybeans	Soy protein concentrate	Soy protein isolate
	Nondehulled	*Dehulled*			
Arginine	93	94	93	99	99
Histidine	90	91	88	97	91
Isoleucine	88	89	84	95	90
Leucine	88	89	86	95	89
Lysine	89-	90	86	95	91
Methionine	91	91	85	94	92
Cysteine	84	87	80	94	82
Phenylalanine	88	89	88	97	92
Tyrosine	90	90	87	96	91
Threonine	85	87	83	94	85
Tryptophan	87	90	82	93	88
Valine	86	88	83	94	89

[a] Data for soy protein isolate measured in weanling pigs (Pahm & Stein, 2007a). All other data measured in growing–finishing pigs (NRC, 1998).

digestibilities of AAs in SPI compared with SBM is that fiber and oligosaccharides are removed from the defatted meals, which may impact the digestibilities of AAs (Smirickey et al., 2002).

The digestibilities of AAs in full-fat soybeans are greater than in SBM (Pahm & Stein, 2007a). The reason for this observation is most likely that the addition of oil to SBM or SPC increases the digestibilities of AAs (Albin et al., 2001; Li and Sauer, 1994). In fact, Pahm and Stein (2007a) demonstrated that adding soybean oil to SBM increased the digestibilities of AA in SBM to levels that were not different from the digestibilities obtained in full-fat soybeans.

The particle size of SBM also influences the digestibilities of AAs, and the digestibilities are improved in SBM having a particle size of 600 microns compared with SBM with a particle size of 900 microns (Fastinger & Mahan, 2003). This observation concurs with the fact that the performance of pigs fed diets based on corn and SBM improves if the particle size is reduced (Lawrence et al., 2003). Microbial phytase does not influence ileal digestibility of AAs in SBM (Traylor et al., 2001), but measured values for the standardized ileal digestibility of AAs are reduced as feed intake is increased (Motor & Stein, 2004). This observation mainly has implications for pigs fed experimental diets used to measure AA digestibility of soybean protein because under commercial conditions, most pigs are allowed ad libitum access to feed.

Phosphorus Digestibility of Soybean Products by Pigs

Historically, values for relative availability of phosphorus rather than digestibility of phosphorus were measured (Cromwell et al., 1993), and relative availability values of 31 and 23% for nondehulled and dehulled SBM, respectively, were reported (NRC, 1998). However, values for the relative availability of phosphorus in other soybean products are not available.

The apparent total tract digestibility of phosphorus in dehulled SBM was reported to be 38% (Bohlke et al., 2005). Apparent total tract digestibility of phosphorus in nondehulled SBM was reported at 48.1 and 34.9% for diets containing approximately 41 and 55% SBM, respectively (Ajakaiye et al., 2003). However, Rodehutscord et al. (1996) measured a value of only 31% for apparent total tract digestibility of phosphorus in nondehulled SBM. Based on these results, the values for relative availability of phosphorus in SBM that are published by NRC (1998) probably are too low, because the apparent total tract digestibility of phosphorus in SBM seems to be 30–40% for both dehulled and nondehulled SBM.

The digestibility of phosphorus in SBM is improved by more than 100% if microbial phytase is added to the diet (Cromwell et al., 1993; Rodehutscord et al., 1996; Traylor et al., 2001). Dietary microbial phytase, therefore, is very effective in improving the digestibility of phosphorus in SBM.

Energy Digestibility of Soybean Products by Pigs

The digestibility of energy in soybean products has not been measured in many experiments, but values for digestible energy (DE) and ME in dehulled SBM of 3,685 and 3,380 kcal/kg, respectively, are published by NRC (1998). These values are in good agreement with recently measured values of 3,660 and 3,410 kcal/kg of DE and ME, respectively (Woodworth et al., 2001), but greater than an average DE value of 3,383 kcal of DE per kg calculated from van Kempen et al. (2006). SBM from soybeans that were not dehulled contains less digestible energy than dehulled SBM (3,490 and 3,180 kcal/kg of DE and ME, respectively), whereas SPC and SPI contain slightly more DE and ME than dehulled SBM (NRC, 1998). However, full-fat soybeans contain more energy (4,140 and 3,690 kcal of DE and ME, respectively) than any of the defatted soybean products. This observation is in agreement with the fact that soybean oil has a high concentration of energy (8,750 and 8,400 kcal of DE and ME, respectively).

Utilization of Soybean Products in Diets fed to Swine

Soybean Meal in Swine Diets

SBM is one of the best protein sources available for swine diets (Shelton et al., 2001), and both dehulled and nondehulled SBM are excellent sources of AAs for swine. However, new varieties of soybeans are constantly being developed. These new varieties have specific nutritional characteristics that influence the quality of the SBM being produced from the beans. Examples of such new varieties are soybeans with higher protein concentration or lower concentrations of oligosaccharides, but only limited information exists about the nutritional values of these varieties as compared with conventional varieties (Pahm & Stein, 2007a). Most of the soybeans that are grown were developed using genetically modified seeds that have specific agronomic traits. However, the nutritional composition and the feeding value of SBM produced from genetically modified beans are not different from the nutritional value of conventional soybeans (Cromwell et al., 2002).

In diets fed to growing–finishing and reproducing swine, SBM may provide all the AAs needed by the animals. However, newly weaned pigs do not tolerate soy protein as well as older pigs (Sohn et al., 1994), and they may develop allergenic reactions followed by immunological responses if they are fed large quantities of SBM (Li et al., 1990; 1991). Therefore the concentration of SBM in diets fed to pigs immediately after weaning should be limited and other protein sources need to be included in these diets. The inclusion rates of SBM can gradually be increased as the pigs grow older, and when they reach a weight of 20–25 kg, SBM can be used as the only protein source in the diet.

Soy Protein Concentrates and Soy Protein Isolates in Swine Diets

SPC and SPI may be used in diets fed to weanling pigs instead of SBM may be used because the ingredients are thought not to elicit antigenic responses in the pigs (Sohn et al., 1994). However, differences may exist among sources of SPCs, and extrusion of SPC may improve the nutritional value (Li et al., 1991). However, the cost of SPI is usually at a level that is prohibitive for use in diets fed to swine.

Soybean Oil in Swine Diets

Soybean oil is recognized as an excellent energy source in diets fed to all categories of swine. In addition, dietary soybean oil may reduce the dustiness of diets fed in meal form and the pelletability of pelleted diets. Addition of fat to diets fed to weanling pigs during the initial two weeks post-weaning usually does not increase performance. However, from approximately day-15 post-weaning and during the remaining nursery period, average daily gain may be improved if soybean oil is added to the diet (Howard et al., 1990; Owen et al., 1996) although that is not always the case (Hoffman et al., 1993; Tokach et al., 1995). Diets containing soybean oil usually have greater energy concentrations than diets containing no soybean oil, and feed utilization is, therefore, often improved if measured on a kg-per-kg basis (Owen et al., 1996). However, if measured on the basis of calories used per unit of gain, adding soybean oil to the diet has no effect (Hoffman et al., 1993).

In diets fed to growing pigs, fat addition often improves daily gain, but that is not always the case for finishing pigs (de la Llata et al., 2001; Overland et al., 1999). Feed utilization is usually not improved if measured on a caloric basis.

Dietary fat in diets fed to lactating sows increases milk fat yield and results in heavier pigs being weaned (Tilton et al., 1999; van den Brand et al., 2000). Soybean oil has been shown to be effective in promoting these improvements (Yen et al., 1991), but to our knowledge, no studies were conducted comparing the effects of soybean oil to the effects of feeding from other fat sources.

Full-fat Soybeans in Swine Diets

Full-fat soybeans may be used in diets fed to pigs provided that they are heat-treated prior to feeding. Because of the relatively high oil content in full-fat soybeans, the energy concentration of diets usually is improved if full-fat soybeans are included. The digestibilities of AAs in full-fat soybeans are greater than in SBM (Pahm & Stein, 2007a), and the concentrations of DE and ME in full-fat soybeans are also greater than in SBM (Woodworth et al., 2001).

Full-fat soybeans are often included in diets fed to nursery pigs and finishing pigs usually do not contain full-fat soybeans because the oil in full-fat soybeans may reduce the quality of the belly of the pigs. Diets containing full-fat soybeans may completely replace SBM in diets fed to growing–finishing pigs without any negative impact on pig performance (Leszczynski et al., 1992). If pigs are offered a diet containing no full-fat soybeans during the final three weeks prior to slaughter, belly quality is not impaired by feeding full-fat soybeans (Leszczynski et al., 1992). Full-fat soybeans may also be included in diets fed to sows and can potentially replace all SBM in gestating as well as lactating diets.

New Soybean Protein Sources in Diets Fed to Pigs

Enzymatic preparation of SBM was shown to remove the antigens in SBM that cause allergenic reactions in weanling pigs. It is, therefore, possible to produce enzyme-treated SBM that is tolerated by weanling pigs. A product produced using this technology is HP 300 (Hamlet Protein, Horsens, Denmark). This product has greater concentrations of protein and AAs than regular SBM because carbohydrates, antigens, and oligosaccharides were removed during the enzymatic treatment (Zhu et al., 1998). The digestibilities of AAs in HP 300 are greater than the digestibilities of AAs in conventional SBM, and most AAs have standardized ileal digestibility values that are similar to SPI and fish meal (Pahm & Stein, 2007b). Inclusion of HP 300 in diets fed to weanling pigs will, therefore, result in pig performance that is similar to that obtained in diets based on animal proteins.

Fermentation of SBM using *Apergillus oryzae* or *Bacillus subtillis* may also remove antigens, antinutritional factors, and oligosaccharides from soybeans or SBM (Hong et al., 2004; Yang et al., 2007). The fermentation partly hydrolyzes the soy proteins, which results in reduced peptide size in fermented SBM (Hong et al., 2004). The fermented SBM contains ~10% more protein than conventional SBM, but the AA sequence is similar to conventional SBM (Hong et al., 2004). The digestibilities of AAs in fermented SBM are similar to conventional SBM (Pahm & Stein, 2007b), but the inclusion of fermented SBM in diets fed to weanling pigs at the expense of conventional SBM was shown to improve pig performance (Feng et al., 2007). Therefore, possibly, fermented SBM may become an attractive ingredient in weanling pig diets in the future.

Conclusion on Soy Products in Diets Fed to Swine

Dehulled solvent-extracted SBM is a highly popular feed ingredient in diets fed to all categories of swine except for newly weaned pigs. The main reason for including SBM in diets fed to pigs is to provide AAs that are required by the animals. The nutrient composition of SBM is relatively constant although the protein and AA concentrations tend to be lower if the soybeans are grown in the Northern regions of the United States rather than in the Central or Southern regions. The digestibilities in pigs of the AAs in SBM have been measured in numerous experiments, and the results showed that the digestibilities are relatively high and constant in various sources of SBM. In contrast, only few reports exist on the digestibility of phosphorus in SBM, and the results are somewhat conflicting. However, the digestibility of phosphorus in SBM is relatively low because most of the phosphorus is bound in the phytate molecule, but it is possible to increase the digestibility of phosphorus in SBM by more than 100% by adding microbial phytase to the diet. Also, there is a need for more information on the concentration of digestible energy in SBM.

Other sources of soybean protein, such as nondehulled SBM and full-fat soybeans, are also valuable protein sources that may replace dehulled SBM. Excellent performance was demonstrated in pigs fed diets containing SPC because of the low concentration of antigens and the high AA digestibility in these products. However, due to the higher costs of these products compared with dehulled SBM, they are not used in diets fed to growing–finishing pigs or sows. Fermented SBM and enzyme-treated SBM recently became available to the industry. These products may potentially replace SPC in diets fed to weanling pigs.

Soybean oil is an excellent source of energy, and diets fed to weanling pigs after day-15 post-weaning and to growing–finishing pigs may be fortified with soybean oil. This usually results in an improvement in average daily gain and no change in the caloric utilization of the feed. If included in diets fed to sows, soybean oil will result in increased weaning weights of the pigs and reduced weight loss of the sows.

Soybean Products In Diets Fed To Companion Animals

A key component of diets fed to companion animals is the protein source that is used in the diets. As an economical source of protein, SBM is commonly included in companion animals diets. However, in 2006, the 1.0 million metric tons (1.1 million tons) used in commercial pet foods represented only 3% of total SBM used by animals in the United States (American Soybean Association, 2007; Fig. 18.1).

For companion animals, SBM is a readily available source of high-quality protein with a balanced AA profile (Grieshop et al., 2003; van Kempen et al., 2002). Moreover, soy protein ingredients have functional properties that make them desirable for use in manufacturing such as absorption, elasticity, and water- and fat-binding properties (Hill, 2003). Unfortunately, SBM also possesses undesirable characteristics such as a low concentration of methionine, high concentrations of trypsin inhibitors, and the presence of flatulence-causing oligosaccharides (Grieshop & Fahey, 2000). Dietary SBM may also cause poor stool consistency (Grieshop & Fahey, 2000). The cat was reported to have greater fecal losses of taurocholate when fed high soybean protein diets (Kim et al., 1995). Table 18.4 summarizes advantages and disadvantages of using soybean products in pet foods.

Soybean Products Used in Pet Foods

Examples of soybean products used in pet foods include SBM, soy flour, SPCs, SPI,

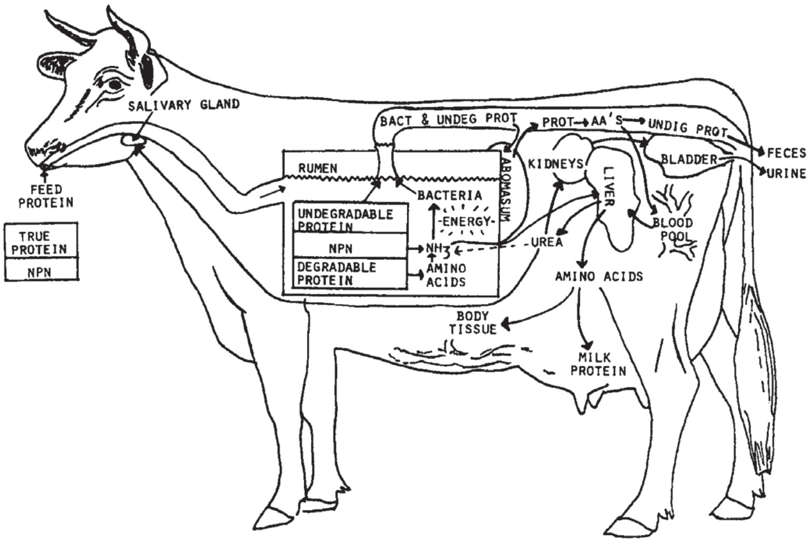

Fig. 18.2. Schematic of protein metabolism in the lactating cow.

and textured vegetable protein. Solvent-extracted SBM contains approximately 44.5% crude protein, 1.4% fat, and 7% crude fiber (NRC, 2006). Soy flour is finely ground SBM and can be used directly or subjected to further processing. Textured vegetable protein is produced by extrusion of defatted soy flour and contains approximately 51% crude protein, 1% fat, and 31% carbohydrates (Hill et al., 2001). Textured vegetable protein from soybeans is commonly included in canned pet foods because it retains the appearance of meat during the canning process. SPIs and concentrates are "purified SBM" made by separating the soy carbohydrates from the proteins (described in detail in the Chapter: *Soy Protein Products, Processing, and Utilization*). Soy protein fractions that contain a minimum of 65% protein are termed *soy protein concentrates*. Table 18.5 summarizes the chemical composition of selected soybean products used in pet foods.

Nutritional Characteristics of Soy Products Used in Pet Food

The soybean is an excellent source of protein and carbohydrates. It is rich in polyunsaturated fatty acids, very low in saturated fats, and contains no cholesterol (Zhang & Laflamme, 1999). However, environmental conditions under which soybeans are grown greatly impact chemical composition and nutrient quality(Grieshop et al., 2003; Grieshop & Fahey, 2001). Because variations in processing conditions can mask both the positive and negative effects of environment, it is critical know the chemical

Table 18.4. Advantages and Disadvantages of Using Soybean Products in Companion Animal Diets [a]

Advantages	Disadvantages
Economical source of protein Readily available and consistent quality	Contains antinutritional factors such as trypsin inhibitors and oligosaccharides
Balanced AA profile complements that of other ingredients, such as corn	Low methionine content; possible increased taurine requirement in cats
Textured vegetable protein retains appearance of meat during canning	Low digestibility Flatulence
Improved product texture Source of protein for vegetarian diets	Poor fecal quality (wet and loose feces) Source of excessive soluble fiber
Source of dietary fiber	Reduces trace mineral availability Allergic reaction to protein Negative connotation for pet owners

[a] From Grieshop and Fahey, 2000.

Table 18.5. Chemical Composition of Soy Protein Sources Used in Pet Foods.

Item	SBM[a]	Soybean, full-fat[b]	Soybean, defatted[a]	SPC1[a]	SPC2[a]	SPC3[a]
DM[c], %	87.4	96.2	92.7	94.9	94.3	94.5
	% of DM[c]					
OM[c]	92.6	–	93.0	93.9	93.0	95.9
CP[c]	56.6	39.6	55.3	72.2	70.4	70.5
Fat[c]	2.5	22.8	2.8	1.1	0.8	3.2
TDF[c]	15.7	–	16.2	21.3	17.5	21.1

[a] Data from Clapper et al. (2001). SBM = soybean meal; SPC1 = soy protein concentrate (traditional aqueous alcohol-extracted SPC); SPC2 = texturized soy protein (extruded SPC); SPC3 = modified molecular weight SPC (low antigen product).
[b] From NRC, 2006. Unit for CP and fat is percentage of DM.
[c] DM = dry matter; OM = organic matter; CP = crude protein; TDF = total dietary fiber.

characteristics of soybeans from different origins when diets are formulated.

Soybean Products as Protein Sources in Pet Diets

Soy protein is typically added to pet foods as a complementary protein in primarily grain-based diets (Hill, 2003). Although SBM contains high-quality protein (Dust et al., 2005), the AA profile of soy protein is not complete. Methionine and cysteine are the limiting AA in SBM in meeting the nutritional requirements of the dog and, especially, the cat (Table 18.6). Soy protein must be combined with a complementary protein to provide all the indispensable AAs that are needed by the animals. Wiernusz et al. (1995) compared five isonitrogenous (11% crude protein) canned dog foods containing 13.5% soybean grits, 13.3% soybean flour, 10.7% SPC, 8.1% SPI, or 8.9% wheat gluten. Diets containing SPC, SPI, and wheat gluten resulted in improved apparent digestibilities of dry matter (84.6, 86.4, and 88.4%, respectively), crude protein (89.8, 89.7, and 93.8%, respectively), and energy compared with diets containing soy grits or soy flour (81.1 and 82.6% for dry matter, and 86.7 and 87% for crude protein, respectively). Fecal output was reduced for all diets except the one containing soy grits, and stool quality was improved by the SPI and wheat gluten diets. These data suggest that the adverse effects reported with soybean product usage may be reduced and the nutritional value of soy improved by further processing the soybean products. Hullar et al. (1998) obtained similar results in castrated adult cats fed a diet containing 20% full-fat SBM, 40% meat meal, and 39% maize in the form of a raw mixture or an extruded pellet. Feeding the raw mixture decreased digestibilities of dry matter, organic matter, crude protein, ether extract, and N-free extract when compared with the extruded diet. However, in a more recent study in dogs, Clapper et al. (2001) showed that neither ileal nor total tract nutrient digestibility was affected by soy protein processing. The authors noted that total tract digestibilities of dry matter, organic matter, and GE were not different among treatments. Yamka et al. (2005) evaluated ileal and total tract nutrient digestibilities of isonitrogenous dry dog foods containing low-oligosaccharide, low-phytate SBM, conventional SBM; low-oligosaccharide, low-phytate whole soybeans; or conventional whole soybeans. They reported an intestinal dry matter digestibility ranging from 80.9% to 74%. Total tract dry matter digestibility was greater ($P = 0.02$) for low-oligosaccharide, low-phytate SBM (87%) than for conventional SBM (84.8%), but no difference existed between the two full-fat soybean diets (average = 83.3%).

Several studies evaluated soy products as pet-food ingredients compared with products of animal origin. Murray et al. (1997) conducted a study comparing the ileal and total tract nutrient digestibility of five isonitrogenous dry dog foods containing defatted soy flour, rendered beef meat and bone meal, fresh beef, poultry by-product meal, and fresh poultry. No differences were observed among treatments in ileal digestibilities of dry matter, organic matter, crude protein, fat, or GE. Bednar et al. (2000) confirmed these results in a study comparing SBM to beef meat and bone meal, poultry meal, and poultry by-product meal. Clapper et al. (2001) compared SBM, soy flour, three SPCs, and poultry meal, and found similar ileal digestibilities of dry matter, organic matter, fat, and GE, but greater ileal crude-protein digestibilities when soy protein-containing diets or SPC-containing diets were compared to the poultry meal diet. No differences in apparent total tract digestibility of dry matter were observed by Murray et al. (1997); however, they found increased organic matter and crude protein digestibilities with diets containing animal by-products (averages = 91.7 and 89.3%, respectively) when compared with the diet containing defatted

Table 18.6. Comparison of Protein and Amino Acid Profile of Soybean Meal and AAFCO Standard for Maintenance of Adult Dogs and Cats

		AAFCO food nutrient profile[a]	
Nutrient[b]	Soybean meal[c]	Dog	Cat
Crude protein	49.2	18	26
Arginine	7.37	2.83	4.00
Histidine	2.67	1.00	1.19
Isoleucine	4.54	2.06	2.00
Leucine	7.81	3.28	4.81
Lysine	6.46	3.50	3.19
Methionine + cysteine	3.08	2.39	4.23
Methionine	1.39	Not specified	2.38
Phenylalanine	4.98	Not specified	1.62
Threonine	3.95	2.67	2.81
Tryptophan	1.39	0.89	0.62
Valine	4.70	2.17	2.38
Taurine	0.00	Not specified	0.38[d]

[a] From AAFCO, 2007. Minimal requirement for maintenance for adult animals.
[b] Protein is in percentage of dry matter. Unit for AA is percentage of protein.
[c] From NRC, 1998.

soy flour (90.2 and 88.3%, respectively). Bednar et al. (2000) confirmed higher total tract organic matter digestibilities with diets containing animal by-products (average = 87.4%) compared with the SBM-containing diet (82.7%), but they found similar total tract digestibilities of crude protein with diets containing SBM, poultry by-product meal, and beef meat and bone meal (82.7, 81.6, and 82.4%, respectively). Clapper et al. (2001) found no differences in total tract digestibilities of dry matter, organic matter, fat, or GE between soy protein-containing diets and the poultry meal diet, but they observed greater total tract crude protein digestibilities when soy protein-containing diets or the SPC diets were compared to the poultry meal diet. In canned dog foods, the use of texturized vegetable protein from soy had a negative effect on nutrient digestibilities. Hill et al. (2001) showed that both ileal and total tract dry matter and crude protein digestibilities decreased linearly with increasing texturized vegetable protein concentration in canned diets. Moreover, texturized vegetable protein led to increased fecal output and fecal moisture (Hill et al., 2001, 2006) in the same way as fecal excretion was greater with SBM dry diets versus animal by-product diets (Bednar et al., 2000; Clapper et al., 2001). Nevertheless, soy flour and SPCs obtained through different processes seemed to improve fecal consistency and reduce fecal output (Clapper et al., 2001).

Several soy products may be used as protein sources in dog foods. In dry extruded diets, both ileal and total tract crude protein digestibilities of soy-containing diets appear to be equal or superior to diets containing animal protein by-products. On the other hand, in canned foods, texturized vegetable protein can reduce dry matter and crude protein digestibilities by dogs, and soy protein sources usually increase fecal output. A lack of information is apparent on the effects of including soy protein sources in diets fed to cats.

Soybean Products as Fiber Sources in Pet Diets

Although soy protein products are commonly added to companion animal diets as a source of protein, some soy products also can be used as sources of fiber or energy (Grieshop & Fahey, 2000). On a dry matter basis, soybean hulls may contain nearly 83% total dietary fiber when unprocessed and up to 85% total dietary fiber after extreme extrusion (Dust et al., 2004). Soybean carbohydrates make up approximately 35% of soybean seed and 40% of SBM dry matter (Karr-Lilienthal et al., 2005). Sunvold et al. (1995) conducted an in vitro fermentation of several fibrous substrates including soybean hulls. Soybean hull fermentation by dog fecal microflora resulted in relatively low organic matter disappearance (<20%) and low total short-chain fatty acid production (<15 mmol/g of substrate organic matter). Nevertheless, in this study, soy hull fermentation data were similar to those obtained with beet pulp fermentation, which is a commonly used fiber source in companion animal diets (Table 18.7). Cole et al. (1999) reported that inclusion of 3.0, 4.5, 6.0, 7.5, or 9.0% soybean hulls in diets fed to dogs had negative effects on apparent digestibilities of dry matter, organic matter, total dietary fiber, and GE, although crude protein and fat digestibilities were unaffected. Cole et al. (1999) also compared diets containing 0, 6.0, 7.5, or 9.0% soybean hulls with a diet containing 7.5% beet pulp. No differences appeared in nutrient digestibility among diets containing soybean hulls or beet pulp. These results are supported by those of Harmon et al. (1999), who also observed a decrease in dry matter, energy, crude protein, and neutral detergent fiber apparent digestibilities with soy fiber- and beet pulp-containing diets compared with diets containing corn or cellulose. Total fecal output was not affected by increased soy hull supplementation, but fecal quality was improved with increasing soy hull concentrations in the diet (Cole et al., 1999).

In dog foods, soy hulls seem to provide a relatively large fraction of readily fermentable fibers, and have a fermentation profile comparable to beet pulp. Moreover, soy hulls have a positive effect on fecal characteristics (consistency and output).

Table 18.7. In Vitro Soy Hull Fermentability by Dog Fecal Microflora[a]

	Organic matter disappearance, %			Total SCFA production, mmol/g substrate OM [b]		
Item	6 h	12 h	24 h	6 h	12 h	24 h
Beet pulp	17.2	17.7	24.5	0.66	0.71	1.96
Soy hulls	14.7	16.0	16.2	0.60	1.02	1.40
SEM	3.1			0.25		

[a] Data from Sunvold et al. (1995).
[b] OM = organic matter; SCFA = short-chain fatty acids.

Antinutritional Factors in Soy Products

Known factors with adverse effects on nutrient digestibility in whole soybeans are trypsin inhibitors and phytate (Zhang & Laflamme, 1999). Phytate has a high affinity for di- and trivalent metals, such as calcium, magnesium, iron, phosphorus, and zinc. The presence of phytate in the diet can decrease nutrient and mineral availability due to the lack of phytase in the gastrointestinal tract of dogs and other monogastric species (Schoenherr et al., 2000; Traylor et al., 2001). Phytate cannot be inactivated by heating, so mineral availability from soy-based diets must be addressed by other means (Zhang & Laflamme, 1999). Yamka et al. (2005) conducted a study evaluating the effect of low-oligosaccharide, low-phytate whole soybeans and SBM on nutrient digestibilities. The authors found no differences in ileal or total tract digestibilities of dry matter, nitrogen, and dispensable AA between treatments. Only histidine and tryptophan digestibilities were lower in low-oligosaccharide, low-phytate whole soybeans compared with conventional whole soybean-containing diets.

Raw soybeans contain numerous trypsin inhibitors. These compounds block the action of trypsin and other enzymes, such as chymotrypsin, elastase, and other serine proteases, which decreases protein digestibility and bioavailability (Liener, 1994). Trypsin inhibitors can be inactivated by moist heat (Osborne & Mendel, 1917), such as extrusion (Alomso et al., 1998). Romarheim et al. (2005) showed that extrusion sufficiently eliminated trypsin inhibitors in SBM-based diets fed to mink (2.7–0.2 mg of trypsin inhibitors/g diet, and 8.3–3.1 mg of trypsin inhibitors/g diet for defatted SBM diet). With similar heating conditions (>116°C) in both extrusion and canning processes, trypsin inhibitors should not be a problem in pet foods.

Physiological and Gastrointestinal Effects of Soy Products

The biggest limiting factor for increasing soybean usage in pet foods is the presence of flatulence-causing oligosaccharides. SBM contains 6–8% sucrose, 3–5% stachyose, and 1–2% raffinose. The colonic fermentation of these nondigestible oligosaccharides can lead to gas production in the gastrointestinal tract of dogs. Genetic manipulation of soybeans resulted in the creation of varieties that contain negligible quantities of raffinose and stachyose. Some studies investigated the digestive response of dogs to diets containing conventional and low-oligosaccharides SBM (Yamka et al., 2005; 2006; Zuo et al., 1996). Yamka et al. (2006) evaluated the effect of conventional SBM, low-oligosaccharide, low-phytate SBM, and poultry by-product meal containing up to 22.4 g/kg stachyose on nutrient digestibility and flatulence (H_2S production). The poultry by-product-based diet had higher dry matter digestibility and digestible energy concentration compared with soy-based diets. No differences were detected for any treatment regardless of protein source or addition of supplemental enzyme for any flatulence component analyses. The authors concluded that diets containing <2.4 g/kg of stachyose and <2 g/kg of raffinose did not alter digestibility or increase flatulence in dogs. Zentek (1995) showed that the in vitro fermentation of SBM and SPC decreased concentrations of H_2S compared with a meat meal-based diet (2.69, 2.57, and 3.28 volume percentage, respectively). These results show that processed or modified soybean products (SPC or low-oligosaccharide SBM) have a positive effect on gas production.

Hill et al. (2006) evaluated the effect of increased soy total dietary textured vegetable protein:beef protein ratio in canned high-fat diets on glucose and insulin responses in dogs. Adding total dietary textured vegetable protein reduced the insulin response during the first 2 h after a meal by 63%. According to the authors, this effect was due to the soy carbohydrates.

Feeding SBM-containing diets is associated with morphological or physiological changes in the gastrointestinal tract of dogs. Dogs fed a soy protein diet (23.5% crude protein) had greater net colonic fluxes of acetate, propionate, butyrate, and total short-chain fatty acids than did dogs fed a meat diet (Hallman et al., 1994). In contrast, dogs fed a casein-based diet had less damage in the colon than dogs fed diets containing SPC (Hallman et al., 1994). In this study, dogs fed the SPC diet had colons that contained more protein and fat than dogs fed diets containing freeze-dried beef or casein, although the colons of dogs fed the casein diet had a greater crypt depth. The effect of several dietary treatments including soy product-based diets on precancerous colon lesions (assessed as foci with aberrant crypts) in rats was evaluated. Among the soy treatments, defatted soy flour and full-fat soy flakes reduced the early stages of colon cancer by inhibiting the formation of foci with aberrant crypts (Thiagarajan et al., 1998).

Conclusion on Usage of Soy Products in Pet-Food Diets

The volume of soybean products used in companion animal diets is significant, and the potential for higher rates of inclusion is great. Soy protein, when combined with other protein sources that contain complementary AA, can provide an economical source of highly available and high- quality protein to companion animals. In the past 10 years, chemical composition of relevant soy products was evaluated. These data indicated a significant variation in chemical and nutritional characteristics among SBM from different U.S. sources or from different countries. This revealed that the nutritive value of SBM was determined not only by the quantity and availability of AAs but also by origin and the processing conditions used in the preparation of the products. Fecal bulk and flatulence are the greatest concerns in promoting the benefits of soy product inclusion to pet owners. Research showed that, at the terminal ileum, soy protein fractions are equal to or superior to animal protein by-products in terms of dry matter and nutrient digestibility. When soybeans are processed beyond the meal and flour forms into SPC and SPI, nutrient digestibility may be increased and the problem with fecal bulk reduced, resulting in fecal characteristics comparable to those of dogs consuming animal protein by-products.

The knowledge about the usage of soybean products in companion animal diets is quite limited compared with the knowledge about using soybean products in diets for poultry and livestock. A limited database exists regarding the effects of soy products on growth performance, gastrointestinal tract characteristics, and physiological events in the dog and cat. Much is known about the protein and lipid components of soy products, but little published information is available on other major components such as carbohydrates. Some future research activity should center on genetically modified soybeans and the resultant products from them. Elimination or reduction of antinutritional factors in soy products (such as antitrypsin and flatulence- causing oligosaccharides) may improve the connotation of soy use and potentially increase demand for soy products by pet-food manufacturers.

Soybean Products in Diets Fed to Beef Cattle

Soybean products are excellent sources of protein and energy for beef cattle. Approximately 7.0% of the SBM utilized in the United States is fed to beef cattle. This is a much smaller portion than the quantities utilized by swine and poultry (Fig. 18.1). The purpose of this section is to describe the reason for this relationship and how recent research may increase the use of SBM in beef cattle diets in the future. With over 40 million growing and finishing beef cattle produced in the United States each year, this is a huge potential market for soybean products. To understand why only 7% of the SBM consumed by livestock and poultry is fed to beef cattle, one has to begin with a discussion of the digestive physiology of ruminants.

Protein Digestion in Ruminant Animals

Ruminants (cattle, sheep, and goats) are unique as food-producing animals because they possess a large fermentation vat called a *rumen*, which is inhabited by billions of bacteria and protozoa. The bacteria in the rumen produce an enzyme complex called *cellulase*, which allows ruminants to get most of their energy from forages and fibrous feedstuffs. As the bacteria digest fiber, they grow and divide, producing bacterial protein. This protein then passes out of the rumen and enters the abomasum (true stomach) and small intestine where it is digested and absorbed. Because rumen microbes produce urease and can combine free ammonia and carbon skeletons to form bacterial AAs, nonprotein nitrogen (NPN) like urea can be converted to animal protein. Consequently, the two major nutrients required for growth and milk production, energy and protein, can come from sources for which humans and nonruminant animals do not compete.

However, most high-producing ruminants require supplemental true protein in their diet for optimum production. Once consumed, protein can be metabolized in one of two ways in the rumen (Fig. 18.2). The undegradable (escape or bypass) protein escapes microbial degradation, passes out of the rumen, and enters the abomasum and small intestine, where the digestible portion is absorbed as AAs. Alternatively, true proteins may be degraded by bacteria to AAs that are deaminated to ammonia and short-chained carbon skeletons or incorporated intact into microbial protein. As is discussed later, SBM is a valuable source of degradable protein that allows bacteria to grow efficiently.

Ruminants are frequently fed diets that contain NPN because the bacteria can convert the ammonia and carbon skeletons produced in the rumen to indispensable and dispensable AAs. NPN sources usually cost 10–20% of the price of SBM on an equal crude protein basis. Consequently, economics encourages the maximal use of NPN that can be converted to bacterial protein. However, the ability of the bacteria to convert NPN to bacterial AAs is dependent on the amount of energy fermented in the rumen. In general, NPN is utilized more efficiently in high-grain diets than in high-forage diets. For the past 25 years, the approach to balancing feedlot diets was to maximize the utilization of urea or other NPN sources and to optimize the utilization of bypass or less-degradable protein sources.

The chemical nature of crude protein in feedstuffs is the primary factor determining how rapidly it is degraded to ammonia or escapes microbial degradation. To compare feedstuffs, feed nitrogen can be divided into NPN, true protein, and unavailable fractions, which Pichard and Van Soest (1977) labeled as the A, B, and C fractions, respectively (Fig. 18.3). The A fraction is rapidly attacked by rumen bacteria and converted to ammonia. Approximately 20% of the crude protein in SBM is in the A fraction and is degraded in the rumen at a rate of 300%/h (NRC, 1996). In contrast, a more undegradable protein source like distillers grains has 6% of the crude protein in the A fraction.

The B fraction is composed of true protein and is usually degraded at a much slower rate than the A fraction (Fig. 18.3). With many feedstuffs, different types of proteins may reside in the B fraction, all with their own degradation rate (B_1, B_2, etc.). Feed proteins are composed of four major types of proteins: albumins, globulins, prolamines, and glutelins. In general, albumins and globulins are the most rapidly degraded proteins, and prolamines and glutelins are more slowly degraded (Sniffin, 1974). Soy protein is relatively high in albumins and globulins. Unfortunately, these fractions are the most rapidly degraded, because they contain the highest concentrations of essential AAs like lysine and arginine (Tamminga, 1979).

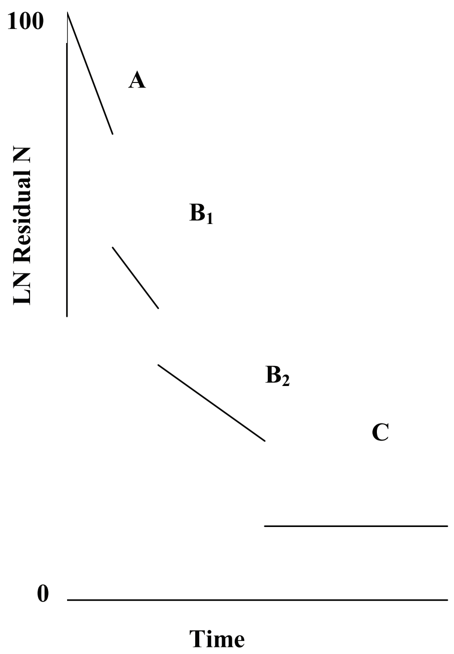

Fig. 18.3. Model illustrating the digestion in the rumen of the A, B_1, B_2, and C protein fractions in feedstuffs.

The unavailable or C fraction nitrogen is estimated by measuring the amount of acid detergent insoluble protein (van Soest, 1991). This fraction is assumed to have zero availability in the rumen and small intestine, and thus has no nutritional value. SBM is a highly digestible protein source with only 2% of the protein in the C fraction (NRC, 1996). In contrast, many slowly degraded protein sources have 10–20% of the protein in the C fraction.

Increasing the Bypass Proteins in Soybean Products

During the past 20 years, scientists sought to improve the nutritional value of SBM for ruminants by reducing the amount of protein in the A fraction and by slowing the degradation rate of the B fraction. Some of the methods explored include formaldehyde treatment, sodium hydroxide treatment, coating with lignin sulfonate, coating with blood proteins, Maillard reactions with xylose or other sugars, and binding with zinc or other metals. Two additional methods include heat and alcohol treatment.

Application of dry heat by baking SBM improved the utilization of SBM by sheep and cattle (Glimp et al., 1967; Sherrod & Tillman, 1962; Thomas et al., 1979). However, roasting has the potential to be a faster and more efficient heat treatment process for SBM. The purpose of this research was to evaluate the effect of roasting temperature on the nutritional value of SBM for beef cattle (Plegge et al., 1985). A commercial continuous flow grain roaster was used to roast SBM to 115, 130, or 145°C. After roasting, the SBM was steeped for 2 h and then cooled to ambient temperatures.

Effects of roasting temperature on nutrient composition, acid detergent insoluble nitrogen, and in situ rate of degradation of the B fraction are shown in Table 18.8. The percentage of the nitrogen recovered as acid detergent insoluble nitrogen increased from 4.1% for the unroasted to 4.9, 4.7, and 15.8%, respectively, for SBM that was roasted at 115, 130, and 145°C, respectively. These data showed that roasting to 130°C would not depress protein digestibility, but going above that temperature could cause a significant reduction in available protein.

In situ rate of protein degradation was estimated by placing samples of the different SBM in small dacron bags and incubating them in the rumen of a fistulated cow for 3, 6, 9, 12, 18, or 24 h. Roasting decreased the rate of in situ nitrogen degradation from 11.3%/h for the unroasted meal to around 4.0%/h for the two lowest roasting temperatures, to only 1.9%/h for the 145°C meal (Table 18.8). These data showed that roasting can dramatically decrease the degradation rate of the B fraction.

To estimate the effect of roasting temperature on the amount of SBM protein escaping ruminal degradation, five ruminal and duodenally cannulated steers were used. The dietary treatments compared were: a urea control, unroasted SBM, and the three roasted SBMs. A balanced 5 × 5 Latin-square design was used with 16-day periods, divided into 10 days for diet adaptation and 6 days for sampling. Lanthanum oxide and chromium-EDTA were used as markers to estimate digesta flow to the small intestine. Steers were fed a diet containing 45% ground corn cobs, 28% ground corn, 10% alfalfa hay, 9% SBM, and minerals and vitamins. All steers were fed 7.1 kg/day, corresponding to 1.8% of body weight.

Soybean meal nitrogen intake averaged 57 g/day, which was 40% of the total nitrogen intake (Table 18.9). Total nitrogen flowing to the duodenum increased linearly ($P < 0.05$) from 112.6 to 147.3 g/day for the unroasted and 145°C SBM, respectively. Bacterial nitrogen flows were not affected by treatment averaging 52 g/day. Soybean meal nitrogen escaping ruminal digestion increased ($P < 0.05$) from 8.3 g/day for the unroasted to 16.5, 20.4, and 27.3 g/day, respectively, for steers fed the 115, 130, and 145°C roasted meals. The SBM nitrogen escaping the rumen increased from 14.7% for the control to 47.3% for the 145°C roasted meal. Acid detergent insoluble N flow also increased with roasting temperature from 8.6 g/day for the unroasted meal to 14.4 g/day for the 145°C meal. These data showed that roasting could dramatically increase the amount of SBM escaping ruminal degradation, but it could also increase the unavailable soy protein.

Table 18.8. Nutrient Composition and In Situ Rate of Degradation of Soybean Meal (SBM) Roasted to Various Temperatures [a]

Item	Control SBM	Roasted SBM 115°C	Roasted SBM 130°C	Roasted SBM 145°C
Dry matter, %	89	93	95	95
Dry matter composition, %				
Ash	7.3	7.6	7.1	7.3
N	8.8	8.9	8.8	8.9
N composition, %				
Acid detergent insoluble N	4.1	4.9	4.7	15.8
Acid pepsin insoluble N	6.8	7.2	7.3	21.0
In situ rate of degradation[b], %/h	11.3[x]	4.3[y]	4.1[y]	1.9[z]
SE[c]	0.0085	0.0058	0.0057	0.0032

[x-z] Values within a row lacking a common superscript letter are different ($P < 0.05$).
[a] Data from Pleege et al. (1985).
[b] Rate of in situ N (non-acid pepsin insoluble) disappearance from 3 to 12 h.
[c] Standard error of rate of degradation.

A reduction in ruminal degradation without increasing the acid detergent insoluble nitrogen can also be achieved using alcohol treatment. A mixture of alcohol and water can change the three-dimensional structure of the soybean proteins. The water penetrates the hydrophilic region of the protein, and the alcohol disrupts the hydrophobic region. This allows a change in the structure of the protein so that more of the hydrophobic AA side chains point to the exterior. This reduces the solubility of the protein in rumen fluid and slows bacterial attack. When combined with moderate heat (78°C), the effectiveness of the treatment process is improved and the alcohol can be recycled (Table 18.10) (Lynch et al., 1987).

Factors Affecting Degradability of Soybean Protein in the Rumen

The first factor that can affect the degradability of soybean protein is rumen pH. Loerch et al. (1983) reported that the disappearance of SBM protein from dacron bags decreased dramatically as the percentage of concentrate in the diet was increased from 20 to 80% (Table 18.11). Sodium hydroxide (3% concentration) was added to the corn to maintain the average rumen pH >6.6 as the corn was increased. When corn was included at 20 and 40% of the diet DM, rumen pHs were similar (above 6.2), and the 12-h disappearance of the SBM was 66.8–79.8%. However, when corn was included at 80% and the pH dropped to 5.5, only 45.2% of the SBM disappeared compared with 81.1% when the pH was 6.64. The changes in degradability are probably due to the isoelectric point of the SBM protein. The isoelectric point of a protein is the pH at which it has no net charge, which should also be the pH where

Table 18.9. Duodenal Nitrogen Flow and Ruminal Escape of Roasted Soybean Meal (SBM) [a]

Item	Urea	Control SBM	Roasted SBM 115 °C	Roasted SBM 130 °C	Roasted SBM 145 °C	MSE
Number of steers	5	4	5	5	5	–
Dry matter intake, g/day	7,110	7,123	7,112	7,117	7,121	–
Organic matter intake, g/day	6,517	6,493	6,480	6,488	6,491	–
N intake, g/day	141	140	141	142	142	–
SBM N intake, g/day	–	57	55	56	58	–
Duodenal organic matter flow, g/day	3,330	3,170	3,208	3,278	3,149	981.1
Total N flow[b], g/day	119.4	112.6	135.8	138.6	147.3	50.4
Particulate N flow[b], g/day	83.6	80.1	91.7	94.6	101.7	41.0
Liquid N flow, g/day	35.9	42.8	44.1	44	45.6	39.0
Liquid ammonia flow[c], g/day	5.4	5.4	6.4	5.6	5.4	0.3
Bacterial N flow, g/day	53.3	48.2	52.2	51.9	53.9	32.2
Plant N flow[b,d], g/day	60.7	69	77.2	81.1	87.9	33.1
Acid detergent insoluble N (ADIN) flow[b,c], g/day	9.5	8.6	9.6	9.8	14.4	0.4
SBM N flow[b,c,e], g/day	-	8.3	16.5	20.4	27.3	33.1
Percentage nitrogen escape [b,f]	-	14.7	29.7	36.2	47.3	121.5

[a] Data from Pleege et al. (1985).
[b] Linear effect of temperature (*P* < 0.05).
[c] Quadratic effect of temperature (*P* < 0.05).
[d] Flow of nonammonia, nonbacterial N.
[e] Flow of plant N minus flow of plant N in the urea basal.
[f] Flow of SBM N divided by SBM N consumed.

the protein is least soluble in rumen fluid, and thus, less susceptible to bacterial attack. The isoelectric point of SBM protein is reached at approximately pH 5.5, which was the average ruminal pH when the 80% rolled high-moisture corn diet was fed. In contrast, degradation of slowly degraded protein sources like blood meal and corn gluten meal (Table 18.11) is not affected by changes in rumen pH. These data help explain why SBM has supported feedlot performance equal or superior to those from cattle fed slowly degraded protein sources in high- concentrate diets. In general, SBM is considered a rapidly degraded protein, but when fed in a diet that produces a pH near its isoelectric point, it becomes a more slowly degraded protein.

The second factor that may influence the degradability of soybean protein in the rumen is if an ionophore, such as monensin, is fed to ruminant animals, it decreases the proteolytic activity of bacteria in the rumen. Poos et al. (1979) and Whetsone et al. (1981) show that the degradability of dietary protein is reduced with monensin

Table 18.10. Effects of Ethanol and Heat Treatment of Soybean Meal (SBM) on In Situ Nitrogen Disappearance and Nitrogen Solubility (%)[a]

Treatment	Time, h 0	3	6	9	12	18	Rate of N loss between 3 and 12 h, %/h	Soluble N, %
	% N remaining in rumen							
SBM[b]	75.5[x]	60.5[x]	50.6[x]	35.7[x]	13.6[x]	6.0[x]	16.9[z]	12.5[x]
ET-23[b]	85.5[y]	78.3[y]	68.9[y]	58.0[y]	29.7[y]	12.3[y]	11.4[y]	7.6[y]
ET-78[b]	92.9[z]	89.9[z]	84.3[z]	74.6[z]	55.4[v]	37.5[v]	4.9[x]	3.7[z]
SEM	0.9	1.4	1.4	1.2	1.5	2.0	0.7	0.9

[v-z] Values within a column lacking a common superscript letter are different ($P < 0.05$).
[a] Data from Lynch et al. (1987).
[b] SBM = untreated SBM; ET-23 = SBM treated in ethanol at 23˚C; ET-78 = SBM treated in ethanol at 78˚C.

Table 18.11. Effect of Concentration of Dietary Corn and Rumen Ph on Nitrogen Disappearance From Dacron Bags [a]

	% Corn							
	20		40		60		80	
Item	NaOH[b]	HMC[c]	NaOH[b]	HMC[c]	NaOH[b]	HMC[c]	NaOH[b]	*HMC*[c]
Ruminal pH	6.78	6.52	6.80	6.27	6.61	6.20	6.64	5.52
Ingredient	% disappearance after 12 h							
Soybean meal	76.2	66.2	79.8	66.8	75.6	47.1	81.1	45.2
Dehydrated alfalfa	69.3	72.3	72.5	62.9	62.8	55.1	71.4	35.6
Blood meal	14.0	15.4	11.6	11.5	10.7	11.6	14.7	15.2
Corn gluten meal	19.1	16.5	19.6	15.0	10.8	15.4	14.0	18.3

[a] Data from Loerch et al. (1983).
[b] Whole shelled corn was treated with 3% sodium hydroxide.
[c] High-moisture corn was rolled prior to feeding.

feeding. Over 95% of the feedlot cattle in the United States are fed an ionophore, with monensin being the most common. The average rumen undegradability value for SBM is 34% with a standard deviation of 12% (NRC, 1996). However, the undegradability value may be increased at least one standard deviation when soluble proteins like SBM are fed in diets that produce a low rumen pH and contain monensin (NRC, 1996). This increases the undegradability value to 46% for soybean protein fed in commercial diets.

The third factor that is believed to influence the degradability of soybean protein in the rumen is that bacterial growth in the rumen can be stimulated by the soluble proteins from SBM. Bacterial growth is rapid as long as AAs are readily available, but when the AA supply is depleted, bacteria must synthesize AAs from ammonia. This requires increased production by the bacteria and results in a slower growth rate (Owens, 1988), and a steady supply of AAs and peptides may be required to achieve optimal fermentation of high-grain finishing diets (Russell et al., 1992). When proteins like SBM are present in the rumen, a continuous supply of AAs is provided, which may result in greater bacterial protein synthesis.

Economic Implications of Using Soybean Meal in Diets Fed to Cattle

In the final analysis, economics dictate how much SBM is fed to growing and finishing beef cattle in the future. Because urea is a less expensive source of nitrogen than SBM, costs per ton of diet always favor diets containing high levels of urea. However, cattle producers need to look at the profit potential from feeding SBM and not just feed cost. They also need to recognize that current management strategies—such as feeding very high levels of concentrate, the use of monensin and other ionophores—, and aggressive implant programs combine to make SBM supplementation more economically competitive.

The potential economic advantage of SBM supplementation compared with urea was demonstrated (Trenkle, 1995). Diets used in these experiments contained only 7% roughage (12% corn silage), steers were implanted aggressively, and the cattle had the genetic potential to gain 1.8 kg/day. The cattle were fed for a constant number of days and sold on a carcass basis when 60–80% of the cattle would grade "Choice." In all cases, feed cost per unit of dry matter was lowest for the diets containing 1.04% urea (Table 18.13).

Feeding Soybean Hulls to Beef Cattle

A second soybean product that has great potential for growing beef cattle is soy hulls, which is a highly digestible fiber source. The nutritional advantage of soy hulls is that they can increase the energy density of the diet without affecting the fiber-digesting bacteria in the rumen. When grains are added to high-forage diets, they can cause a shift in the bacterial population in the rumen or lower the pH so that less of the fiber is digested. Consequently, soy hulls are equal to corn as an energy source in grazing situations or when high-forage growing diets are fed. For example, supplementing steers grazing tall fescue with 1.8 kg/day of corn or soy hulls increased gains by 0.2 kg/day (Kerley & Williams, 1995). Although cost/kg of gain was increased with supplementation, total weight gains per steer were increased by 40 kg over the 160-day grazing period (Table 18.14). The extra weight gain is worth $60 per head, and soy hulls will likely become more popular as an energy source for growing beef cattle in the future.

Table 18.12. Effect of Dietary Nutrition Source and Concentration on Performance of Finishing Steers Fed Diets Based on Dry-Rolled Corn[a]

	Urea		SBM[b]		CSM[b]	
Item	1.93% N	2.24% N	1.93% N	2.24% N	2.24% N	SEM
Initial weight, kg	334	336	335	335	335	0.8
Final weight[c], kg	499	499	515	527	523	6.0
Day 0–132						
Dry matter intake, kg/day	9.82	9.33	9.87	10.02	10.34	0.29
Average daily gain[d], kg	1.25	1.24	0.136	1.46	1.42	0.05
Gain:feed[e]	0.128	0.133	0.139	0.145	0.137	0.003
Day 70–132						
Dry matter intake, kg/day	9.87	9.65	10.02	10.04	10.61	0.36
Average daily gain[d], kg	1.65	1.64	1.76	1.85	1.79	0.10
Gain:feed[e]	0.167	0.170	0.178	0.184	0.169	0.006
Day 70–132						
Dry matter intake, kg/day	9.77	8.96	9.73	10.00	10.09	0.37
Average daily gain[d], kg	0.80	0.79	0.91	1.02	1.00	0.08
Gain/feed[e]	0.083	0.088	0.093	0.102	0.100	0.006
Adjusted performance[f], day 0–132						
Average daily gain[g], kg	1.35[y]	1.24[x]	1.41d[yz]	1.51[z]	1.51[l]	0.04
Gain:feed[d]	0.137	0.130	0.144	0.151	0.146	0.004

[x-z] Data within a row lacking a common superscript letter are different ($P < 0.05$).
[a] Data from Milton et al. (1997).
[b] Supplemental N source: SBM = soybean meal; CSM = cottonseed meal.
[c] Final weight shrunk 4%.
[d] Urea vs. SBM ($P < 0.05$).
[e] Urea vs. SBM ($P < 0.10$).
[f] Average daily gain and gain:feed calculated using final weight = hot carcass weight divided by 0.63.
[g] Interaction between dietary N source and N concentration ($P < 0.05$).

Soybean Products In Diets Fed To Dairy Cattle

Soybean products are widely used in dairy cattle nutrition. The principal products used are SBM (Firkins & Fluharty, 2000), full-fat soybeans (Grummer & Rabelo, 2000), and soybean hulls (Titgemeyer, 2000). Readers are referred to those reviews for additional background and summation of older scientific literature. Little soybean oil is used directly in feeding dairy cattle, partly because of its highly unsaturated fatty acid profile (which can disrupt fermentation of fibrous carbohydrates in the rumen), but mainly because it is usually more expensive than other commodity fats. Soy protein products also are used as components of "alternate protein" milk replacers for young calves, the main products being soy flour, SPC, and SPI (Lallès, 2000).

Table 18.13. Economic Analysis of Feeding Soybean Meal (SBM) to Steers Implanted With Estradiol and Trenbolone Acetate [a,b]

	Diet			
Item	1.04 Urea	5% SBM	10% SBM	SBM-Urea[c]
Experiment 1—Implanted				
Feed DM, $/45.45 kg	4.81	5.08	5.29	4.99
Feed cost of gain, $/45.45 kg	31.01	30.53	32.21	30.01
Total cost, $/steer	809.00	816.52	827.80	816.32
Profit, $/steer	47.14	66.98	57.98	68.32
Experiment 2—Nonimplanted				
Feed DM, $/45.45 kg	4.81	5.08	5.29	
Feed cost of gain, $/45.45 kg	32.59	32.50	35.55	
Total cost, $/steer	862.91	866.49	883.44	
Profit, $/steer	26.27	26.13	22.86	
Experiment 2—Implanted				
Feed DM, $/45.45 kg	4.81	5.08	5.29	4.97
Feed cost of gain, $/45.45 kg	27.26	28.24	28.49	27.01
Total cost, $/steer	883.16	890.73	900.34	889.21
Profit, $/steer	90.40	97.65	107.42	101.45

[a] Data from Trenkle (1995).
[b] Based on feed prices of corn $98.21/metric ton; corn silage, $27.50/metric ton; molasses, $110/metric ton; SBM, $220/metric ton; urea, $0.286/kg; dicalcium phosphate, $0.352/kg; and all other additives, $0.44/kg. Other costs were implants, $3.30/dose; nonfeed, $0.35/day; and purchase price of steers, $1.72/kg. Selling price of carcasses was $2.51/kg.
[c] Diet changed from 10% SBM to 1.04% urea at 56 and 62 days in Experiments 1 and 2, respectively.

Table 18.14. Use of Soy Hulls as an Energy Supplement for Backgrounding Steers [a]

Treatment [b]	Average daily gain, kg/steer	Cost of gain, $/kg	Total gain, kg
Fescue	0.7	0.38	109[x]
Corn	0.9	0.49	141[y]
Soy hulls	0.9	0.48	149[y]

[x, y] Values within a column lacking a common superscript letter are different ($P < 0.05$).
[a] Data from Kerley and Williams (1995).
[b] Fescue = grazed tall fescue pastures for 160 days; Corn = grazed tall fescue pastures plus fed 1.8 kg of corn per steer/day; Soyhulls = grazed tall fescue pastures plus fed 1.8 kg of soybean hulls per steer/day.

Protein Utilization in Dairy Cattle

Protein is needed as a source of absorbable AAs in ruminant animals just as in monogastric animals, but the presence of the complex ruminant stomach complicates protein supply considerably. In the rumen, resident microorganisms (bacteria and protozoa) anaerobically ferment carbohydrates, such as cellulose and starch, producing volatile (or short-chain) fatty acids that are absorbed and used by the animal as energy sources. Simple NPN sources, such as ammonia, along with dietary true proteins that are degraded by the rumen microbes, are used as the nitrogen source for synthesis of microbial proteins needed by the rapidly growing microbial population. The microbial cells are washed out of the rumen with the digesta, and serve as a major protein source of digestible AAs for the host animal. The portion of dietary protein and NPN needed for the microbial population is defined as rumen-degradable protein (RDP; NRC, 2001).

Not all dietary proteins are degraded by the microbial population, and some pass unaltered or with minimal alteration into the small intestine where they are digested much as in a nonruminant animal. Dietary proteins that are not degraded by the ruminal microbes are referred to as rumen-undegradable protein (RUP; NRC, 2001). This fraction also is sometimes referred to as *escape* or *bypass* protein. The total amount of protein that reaches the intestine for digestion is the sum of microbial protein and RUP, and is called *metabolizable protein* (MP; NRC, 2001). This is the actual supply of digested proteins that furnishes AAs to the animal.

Ruminant animals that are essentially at maintenance, growing very slowly, or producing only small amounts of milk can meet virtually their entire AA requirements from microbial protein if moderately fermentable feeds are fed in properly balanced diets. However, as productivity increases, rumen microbial protein supply becomes inadequate to provide all the protein needed by the animal. This deficiency is particularly true for high-producing dairy cows. For example, a 650-kg Holstein cow producing 50 kg of milk with 3.6% fat daily requires a total of 3.25 kg of MP (NRC, 2001). A diet formulated for this cow would require about 2.8 kg of RDP daily and about 1.8 kg of RUP daily (NRC, 2001). Depending on the type and quality of forages available, as well as supply of various by-product feeds, such a cow might be fed 3–5 kg of soybean meal daily as part of the strategy to meet those large protein requirements.

Soybean Meal in Diets Fed to Dairy Cattle

SBM is the most widely used protein supplement for dairy cattle in North America and much of the world. Reasons for the dominance in the market include high nutritional quality, consistency, widespread availability, and cost-competitiveness. SBM usage by the dairy industry in the United States is estimated to be only about one-third of the total potential protein utilization if all supplemental protein was supplied by SBM (Clark & Bateman, 1999).

SBM added to diets for dairy cattle supplies both RDP and RUP. The proteins in typical solvent-extracted SBM are generally ~65% degradable in the rumen (NRC, 2001). Ruminal proteolysis of SBM results in formation of peptides, AAs, and ammonia, all of which may be utilized for growth by particular species of microorganisms in the rumen. This value is not a constant, however, and will be affected by several variables, including cow factors such as the amount of feed intake and rumen pH. In addition, various chemical- or heat-processing methodologies can be applied to alter the protein degradation characteristics of SBM.

As feed intake increases, rates of digesta passage through the digestive tract also increase (NRC, 2001), which decreases the time that SBM is available to the microbial population in the rumen, and therefore, increases the RUP value. Lower pH in the rumen (e.g., 5.8–6.0 instead of 6.0–6.2) also increases the RUP value because the proteins become less soluble as the ruminal pH approaches the isoelectric point of soy proteins; therefore, the proteins are less susceptible to microbial proteolysis. The practical significance of these principles is that RUP values for soybean meal are greater for high-producing cows consuming large amounts of feed than for animals near maintenance (Ipharraguerre & Clark, 2005).

A variety of chemical and heat treatments can be applied to SBM during processing that will increase the RUP values (Firkins & Fluharty, 2000). Treatment of SBM with aldehydes causes cross-linking between peptide chains, thereby decreasing protein solubility and microbial degradation. Formaldehyde has been used most commonly and is effective in decreasing protein degradability. However, toxicity concerns make this treatment less desirable in many countries. Lignosulfonate treatment involves a heat-induced chemical reaction between xylose in sulfite liquor (a waste product from paper manufacture) and AA residues in SBM. The result is the formation of early Maillard products (Friedman, 1996) that decrease solubility of the protein and hence increase resistance to microbial breakdown.

Additional heat applied during processing of SBM is a commonly used approach to manipulate the RUP value. Increasing heat causes more formation of Maillard-type cross-linkages between amino groups (especially lysine) and carbohydrates within the SBM, which decreases solubility and microbial access for proteolysis. As long as the protein is not heated too extensively so that Maillard reactions are irreversible, the protein still can be digested in the acidic abomasum (true stomach) and the enzymatic environment of the small intestine (Firkins & Fluharty, 2000). Several heating processes are used commercially to produce SBM with greater RUP, including screw pressing, extruding, roasting, and toasting. A variation is production of a heat-treated SBM–hulls combination. SBM is combined with soybean hulls in a 10:1 ratio, water is added to bring total moisture to 30–50%, and the mixture is cooked at 95°C until final moisture is between 12–16% (Borucki Castro et al., 2007).

A recent experiment compared solvent-extracted SBM with screw-pressed SBM, lignosulfonate-treated SBM, and SBM–hulls product (Borucki Castro et al., 2007).

The RUP estimates were 42, 68, 62, and 65%, respectively, indicating that all treatments were effective at decreasing the amount of soy protein degraded in the rumen relative to solvent-extracted soybean meal. Ipharraguerre et al. (2005) also showed that lignosulfonate treatment and screw press treatment resulted in increased passage of feed protein to the small intestine.

Heated SBMs are widely used for feeding high-producing dairy cows because of the challenge in providing adequate MP to these cows. Animal protein sources, such as meat and bone meal, were once widely used to supply RUP with good AA balance in diets for dairy cows. However, restrictions on the use of animal proteins in North American and European Union markets severely limited the use of these animal protein supplements. Use of heated or chemically processed SBM to increase dietary supply of RUP for high-producing dairy cows is likely to continue to increase to attempt to meet the AA requirements for copious milk production.

Unfortunately, substitution of more expensive altered proteins does not always lead to improvements in milk production, as summarized by Ipharraguerre and Clark (2005) on the basis of a large meta-analysis of experiments that tested dietary inclusion of high-RUP supplements. This lack of response was confirmed directly in more recent experiments. For example, Colmenero and Broderick (2006) found that solvent-extracted SBM resulted in similar milk yields as replacement with screw-pressed SBM. Possible reasons for the lack of expected improvement were summarized (Ipharraguerre & Clark, 2005) and may include reductions in microbial protein synthesis, decreased feed intake, or lack of improvement in limiting AAs in the intestine.

Similar to the general scheme for protein digestion, AA nutrition in ruminants is also complicated by the existence of the rumen. Among oilseed meals, SBM has the greatest content of indispensable AAs (NRC, 2001). However, the AA profile of proteins in RUP may be altered as a result of preferential degradation of certain AAs in the rumen (Borucki Castro et al., 2007). A fundamental challenge with use of proteins intended to increase RUP supply is that they are supplemented in small proportions relative to the total amount of microbial protein reaching the intestine (Ipharraguerre & Clark, 2005). The AA profile of microbial proteins is essentially constant and of very high nutritional value for milk production (NRC, 2001). In the RUP fraction of SBM, methionine may be limiting for optimal performance (NRC, 2001). Supplemental rumen-protected methionine products are often used in conjunction with SBM to balance the AA profile reaching the intestine.

Full-fat Soybeans in Diets Fed to Dairy Cows

While most soybeans are processed to extract the oil for food uses and to produce SBM for animal feeding, whole full-fat soybeans are an attractive and widely used feedstuff for dairy cows. The high protein concentration of the whole bean coupled with its high-fat concentration results in a feed rich in both protein and energy. While some soybeans are fed raw, most commonly the soybeans are heat-treated to inactivate urease and trypsin inhibitors and to decrease protein degradability (Aldrich et al., 1995). The most widely used treatment is roasting, in which the beans are passed through a forced-air oven or a flame in a rotating drum. Typically, soybeans are heated in a drum roaster to a 146°C exit temperature and then allowed to steep for 30 min before cooling. Optimal heating in forced-air ovens is 140°C for 120 min, 150°C for 60 min, or 160°C for 30 min (Clark & Bateman, 1999; Grummer & Rabelo, 2000). Because of the greater variability in heat penetration in whole beans relative to SBM, variation in the RUP content of whole beans is greater than that for SBM. Ipharraguerre et al. (2005) reported that whole roasted soybeans increased the intestinal supply of feed protein compared with a similar amount of protein only from solvent-extracted SBM.

Whole soybeans also can be heat-treated by extrusion, although this process results in greater rupture of oil-containing vesicles and increases the availability of oil in the rumen. More rapidly available unsaturated oil can result in decreased fiber digestion, lower feed intakes, and depression of milk fat synthesis at lower inclusion rates than with whole roasted soybeans (Grummer & Rabelo, 2000). Where available economically, roasted soybeans are widely used to provide protein and some additional fat to the dairy diet.

Soybean Hulls in Diets Fed to Dairy Cows

Soybean hulls are a by-product of soybean processing and are an excellent supplemental feed for dairy cattle. Because they are low in lignin, the cellulose is highly digestible in the rumen, and fermentation rates are rapid. Soybean hulls were used to replace forage and to replace cereals in concentrates (Titgemeyer, 2000). While soybean hulls ferment differently than starchy concentrate feeds, they cannot replace fibrous forages completely because they do not have sufficient structural fiber to stimulate rumination and maintain rumen pH. Conversely, excessive replacement of starch with soybean hulls may limit production of microbial protein and milk components (Titgemeyer, 2000).

Ipharraguerre and Clark (2003) reviewed the literature on use of soy hulls for dairy cows. They concluded that soybean hulls can replace corn grain to supply ~30% of the dry matter in high-grain diets without negatively affecting either the fermentation or digestion of nutrients in the gastrointestinal tract or the performance of dairy cows. They also concluded from the data that soybean hulls might successfully replace forage to supply up to 25% of the dry matter in the diets of dairy cows as long as the supply of effective fiber remains adequate after including the soybean hulls in the diets. In experiments designed to test these predictions, Ipharraguerre et al. (2002a,b) replaced corn grain with soy hulls to supply 10, 20, 30, or 40% of dietary dry matter. Inclusion of more than 30% soy hulls decreased milk yield despite similar passage of AAs to the small intestine.

Soy Proteins in Milk Replacers for Young Calves

As milk proteins continue to increase in price, manufacturers of milk replacers strive to find lower-cost proteins that will provide adequate growth and maintain health in young dairy calves. Because of the generally good AA profile, soybean proteins have long been considered as an alternate protein to replace milk proteins in young calf nutrition. However, replacement of milk proteins with soy proteins results in inferior growth performance and often impaired health. Similar to young nonruminants, the pre-ruminant calf is sensitive to trypsin inhibitors and the indigestible oligosaccharides found in raw soy. Like young pigs, calves are markedly susceptible to antigenic proteins (primarily β-conglycinin but also glycinin, α-conglycinin, Bowman-Birk inhibitor, and lectins; Lallès, 2000) present in soybean proteins. In contrast to young pigs, however, these allergenic responses persist in calves (Lallès, 2000). Indigestible carbohydrates and many of the offending allergens can be removed by hot aqueous ethanol processing during the production of SPC. However, even good quality feed-grade SPCs do not restore growth to levels comparable to milk proteins (Drackley et al., 2006). Although high-quality SPIs can result in satisfactory performance relative to milk proteins (Lallès, 2000), their higher cost, attributable to the additional processing steps, negates much of the potential advantage from replacing milk proteins. Moreover, many of the SPIs available to the feed industry are off-specification or low-quality materials not suited for the human market.

Reasons for the poor calf performance on soy proteins remain unidentified. Antinutritional factors and antigenic proteins present in raw soybeans are greatly decreased by the hot aqueous ethanol treatment involved in the production of SPC, yet adverse effects on growth and intestinal function still occur when SPC is fed to calves (Lallès, 2000). Changes in intestinal histomorphology occur when calves are fed SPC (Drackley et al., 2006) as well as soy flour (Kilshaw & Slade, 1982). The cellulose and hemicellulose present in SPCs may increase villus abrasion and cell desquamation and also increase mucus loss in the terminal small intestine (Leterme et al., 1998). In addition to alterations in villus size, a variety of other intestinal abnormalities was observed in calves fed low-antigenic soy protein products, including decreases in protein synthetic capacity (Grant et al., 1989), mucosal digestive enzyme activities (Grant et al., 1989; Montagne et al., 1999), and absorptive capacity (Grant et al., 1989) and increases in mucin secretion (Montagne et al., 2000), immune activation (Lallès, 2000), and specific endogenous protein loss (Montagne et al., 2001).

Plant-based proteins, such as soy, have high true digestibilities but lower apparent digestibilities because specific endogenous protein losses at the ileum are increased (Montagne et al., 2000, 2001). Montagne et al. (2003) suggested that resistant dietary oligopeptides may interact with intestinal mucosa to stimulate endogenous protein secretion. SPC increased ileal flow of diet-specific host protein (Montagne et al., 2001), which would increase dietary protein requirements by about 2 g/day for calves fed typical amounts of milk replacer (Drackley et al., 2006). Consequently, it is unlikely that intake of protein limits growth of calves when that occurs. Although dietary contents of lysine and methionine were equalized in most experiments, it is possible that another indispensable AA, such as threonine, (Kanjanapruthipong, 1998) might limit growth relative to whey proteins.

Regardless of the mechanism, average daily gains and gain:feed ratios usually are lower than milk-fed controls when calves are fed milk replacers containing a substantial amount of protein from soybeans. Identification of factors limiting calf performance when soy-containing milk replacers are fed would be an enormous benefit to both the dairy and soybean industries.

Overall Conclusions

Soybean products are primarily used in diets fed to poultry, livestock, and companion animals to supply indispensable AAs to the diets. The AA composition in SBM and other soybean products complements the AA profile in corn and other cereal grains. This is particularly important in diets fed to poultry and pigs, where lysine is often the first limiting AA. Soy protein also contains relatively high concentrations of arginine that is needed in poultry diets, and in tryptophan that is often limiting in diets fed to swine. Dehulled SBM may supply all AAs other than those supplied by the cereal grains in diets fed to poultry and pigs heavier than 20–25 kg. In diets fed to younger pigs, SPC may be used while SBM is slowly introduced during the post-weaning period. Full-fat soybeans are not used as frequently as SBM, but may be used as a total or partial replacement for SBM in diets fed to pigs and poultry. Soy protein may also supply a large proportion of the AAs needed in diets fed to cats, dogs, and ruminant animals. Soy oil, if available at a competitive price, may be used to increase the energy concentration in diets fed to pigs and poultry. In contrast, soybean hulls are usually not used in diets fed to monogastric animals, but they may be used as a valuable fiber source in diets fed to ruminants.

All soybean products, except soybean oil, fed to monogastric animals and pre-ruminant calves need to be heat-treated prior to usage because of the presence of protease inhibitors and lectins in soybeans. Care must be taken to make sure that enough heat is applied for a complete inactivation of these factors, but the heating should not be excessive because that may reduce the digestibility of certain AAs, and lysine in particular. However, if properly heat-treated, the AAs in soybean proteins are usually well digested by all groups of animals. In contrast, the phosphorus in soybean products has low digestibility to most monogastric animals because most of it is bound in the phytate complex. The addition of microbial phytase, however, may improve the phosphorus digestibility by more than 100%.

The usage of soybean products may be increased in the future if modifications to the products can be made. A lower concentration of oligosaccharides will be beneficial to the poultry industry because it may increase the digestibility of dietary energy. A reduced concentration of oligosaccharides may also reduce the flatulence-enhancing properties in soy products, which may increase the usage of soy products in the pet-food industry. Likewise, the usage of soybean proteins in milk replacers to young dairy calves may be increased if varieties with lower concentrations of oligosaccharides and antigens are developed. In the swine industry, the main concern is also the presence of antigens in SBM that prevents the usage of large quantities of conventional SBM in diets fed to newly weaned pigs. Development of soybeans with a reduced concentration of antigens, therefore, will increase the utilization of SBM to this category of swine. The development of enzyme-treated SBM and fermented SBM also has the potential to increase the usage of soy products in diets fed to weanling pigs. The greatest potential for increased usage, however, is by the beef cattle industry that potentially could increase the usage of both SBM and soybean hulls. However, more education on the usage of soybean products to cattle producers may be needed for this to happen.

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