for growth of soy usage in diets for companion animals and in aquaculture requires that problems in soy use for those species be solved through research.

Given the importance of past and future research in positioning soy as the dominant protein source for animal feeding and the importance of soy utilization by animals in driving worldwide demand for soy, the Soy in Animal Nutrition Symposium was designed as a key component of the World Soybean Research Conference VI and Global Soy Forum '99 held in Chicago, IL, USA from August 4–7, 1999. The panel of speakers and authors was selected to provide a cutting-edge review of state-of-the-art soy use relative to their expertise and species of interest. These leading scientists were commissioned to evaluate critically our current knowledge of aspects of soy use in animal nutrition and to identify areas in which additional research would be fruitful. The result of their efforts is presented in this volume. The authors have provided a wealth of information that defines the status of the use of soy products in animal nutrition as we enter the third millennium.

In addition to the authors of these chapters, several others deserve recognition for making this volume possible. First, the vision and impetus for this research symposium were provided by Dr. Robert Easter, Professor and Head of the Department of Animal Sciences at the University of Illinois. Dr. Neal Merchen of the same Department served as Chair of the organizing committee for the symposium. As members of the organizing committee, Drs. David Baker, Larry Berger, George Fahey, Jr., and Carl Parsons served advisory roles in the development of the content of the symposium and proceedings. Ms. Amy Kemp of the Federation of Animal Science Societies provided excellent technical editing and supervision of the design of the final product. The symposium was facilitated by Dr. Harold Kauffman of the University of Illinois with assistance from the staff of the National Soybean Research Laboratory, the University of Illinois, and the Global Soy Forum. Finally, the editor wishes to acknowledge the Department of Animal Sciences in the College of Agricultural, Consumer, and Environmental Sciences, University of Illinois, for providing the resources and intellectual environment to facilitate successful completion of a task of this magnitude.

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Nutritional Constraints to Use of Soy Products by Animals

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The development of solvent-extracted soybean meal (SBM) revolutionized animal production throughout the world. Soybean meal is easily the most important contributor of dietary amino acids for food production from the poultry, swine, and aquaculture sectors of agriculture. It accounted for 62% of total world protein meal consumption in 1996. In the U.S., use of SBM for animal feeds in 1996 was proportioned in the following manner: 52% to poultry, 29% to swine, 7% to beef cattle, 6% to dairy cattle, and 6% to other species (Chandler, 1999). Higher protein soy concentrates and soy isolates are also being used in certain specialized diets for both baby pigs and companion animals.

This review will focus on the virtues of SBM as an animal feedstuff and will also cover some of the imperfections of SBM as a feed ingredient. Because poultry and swine account for over 80% of both domestic and worldwide SBM consumption, these species will be emphasized.

Protein Quality of SBM

The popularity of SBM as an oilseed for poultry and swine is attributed primarily to the fact that it is a very rich source of both lysine and tryptophan. Indeed, SBM is a near perfect complement to corn when the two are combined in a manner that meets the minimal lysine requirement for a given physiological function. Table 1 shows the true digestible amino acid composition of dehulled SBM for broiler chicks and pigs. Also shown are calculated ratios to lysine of each essential amino acid in SBM in comparison with ideal amino ratios for young chicks and pigs (Baker, 1997; Emmert and Baker, 1997). No other oilseed meal compares with SBM in its digestible lysine concentration. (Canola meal is a distant second.) This fact is true whether digestible lysine concentrations are calculated as percentages of the air-dry ingredient or as percentages of the protein.

In practice, both poultry and swine are fed diets that are based almost entirely on corn and SBM. Generally, corn and SBM are fed in proportions that will satisfy the lysine requirement of each species. It can be noted from Table

TABLE 1. Amino acid (AA) composition of dehulled soybean meal (SBM) and AA ratios to lysine compared with ideal AA ratios for broiler chicks and pigs

AA	Broiler chicks (0 to 3 wk of age)			Pigs (10 to 20 kg BW[a])		
	True digestible AA, %[b]	Ratio to lysine, %	Ideal ratio, % of lysine[c]	True digestible AA, %[d]	Ratio to lysine, %	Ideal ratio, % of lysine[c]
Lysine	2.75	100	100	2.72	100	100
Methionine	.62	23	36	.61	22	30
Cystine	.61	22	36	.64	24	30
TSAA[d]	1.23	45	72	1.25	46	60
Threonine	1.63	59	65	1.61	59	65
Tryptophan	.55	20	16	.59	22	17
Valine	2.07	75	77	2.00	73	68
Isoleucine	2.01	73	67	1.92	71	60
Histidine	1.13	41	35	1.16	43	32
Phenylalanine	2.20	80	55	2.13	78	50
Tyrosine	1.67	61	50	1.64	60	45
TAAA[e]	3.87	141	105	3.75	138	95
Arginine	3.20	116	105	3.24	119	42
Leucine	3.37	123	109	3.26	120	100

[a]BW = body weight.
[b]True digestible AA concentration in SBM for chicks, expressed on an air-dry (90% DM) basis (Rhodimet Nutrition Guide, 1993; NRC, 1994).
[c]Baker (1997) and Emmert and Baker (1997).
[d]True digestible AA concentration in SBM for pigs, expressed on an air-dry (90% DM) basis (NRC, 1998).
[e]TSAA = total sulfur AA.
[f]TAAA = total aromatic AA.

1 that SBM alone does not meet the ideal ratios of sulfur amino acids (SAA), threonine, and valine for broiler chicks. However, when combined with corn, which is low in lysine and tryptophan but rich in SAA, in proportions to meet the lysine requirement, more than adequate levels of both threonine and valine are provided; SAA are still deficient (Fernandez et al., 1994). Thus, supplemental DL-methionine is added to virtually all corn and SBM poultry rations. For pigs, both SAA and threonine in SBM do not meet the ideal ratios for these amino acids, but, unlike the situation with poultry, the ideal ratio of SAA to lysine is much lower. Therefore, corn and SBM diets formulated to meet the lysine requirement also meet the minimal needs for both SAA and threonine (Baker, 1997).

There is actually more digestible lysine in the protein of SBM (about 6% of CP) than is required (about 5% of CP) for both chicks and pigs. Because cereal grains are uniformly deficient and first-limiting in lysine, however, the relative excess of lysine in SBM is advantageous because it allows satisfaction of the digestible lysine requirement at a lower CP level. The excess tryptophan in SBM is also advantageous, particularly for pigs, because corn protein is severely deficient in this amino acid. Also, not to be discounted, the true digestibility of both lysine and tryptophan in SBM is higher than that of most competing meals, such as meat meal and canola meal. Canola meal does have one advantage over SBM in that its protein has higher levels of digestible SAA than SBM. Thus, in a head-to-head protein quality comparison (at 10% CP) in young chicks, when either SBM or canola meal furnishes the entire quantity of dietary protein in a semipurified diet, canola meal will produce a slightly higher protein efficiency ratio (PER) value than SBM (Baker et al., unpublished data).

Protein quality studies with SBM in our laboratory (Baker and Emmert, 1997) have demonstrated how the protein quality of SBM can be improved by supplementation with methionine, threonine, and valine. Graded levels of SBM protein (10, 14, 18, 22, and 26% CP) were added isocalorically to semipurified diets that were either devoid of or fortified with methionine, threonine, and valine. The results of this study (Figure 1) show that amino acid fortification improved weight gain substantially at the three lowest levels of dietary protein and that maximal weight gain occurred at 18% CP in amino acid-fortified diets but at 26% CP in diets containing unfortified SBM. Voluntary feed intake increased in chicks fed unfortified SBM protein between 10 and 22%, but it actually <u>decreased</u> at this same range of protein in chicks fed SBM fortified with its limiting amino acids. These divergent feed intake changes frequently occur when comparing high quality proteins (fortified SBM) with lower quality proteins (unfortified SBM). Thus, the drive to meet the need for SAA apparently caused chicks fed the amino acid-deficient diets to consume more feed voluntarily as the protein level was increased.

The efficiency of protein utilization for weight gain (PER) is higher for chicks fed fortified SBM than for those fed unfortified SBM until 26% CP is reached, at which point the PER values reach their lowest point (Figure 2).

Because PER is a reflection of both overcoming deficiencies and accommodating amino acid excesses, the PER values decrease, regardless of amino acid fortification, in a near linear fashion as protein level increases. Studies involving PER assessment are generally done with rats; the protein is set at 10%. Casein is usually included as a positive control, and, with casein fed to weanling rats, PER is maximized at 10% CP. With unfortified SBM fed to chicks, however, PER is not maximized at 10% CP. Another chick study in our laboratory evaluated protein from unfortified SBM at 3, 6.5, 10, 13.5, and 17.0%, and in that study, PER was highest at 3% CP and declined as protein increased (Baker and Emmert,
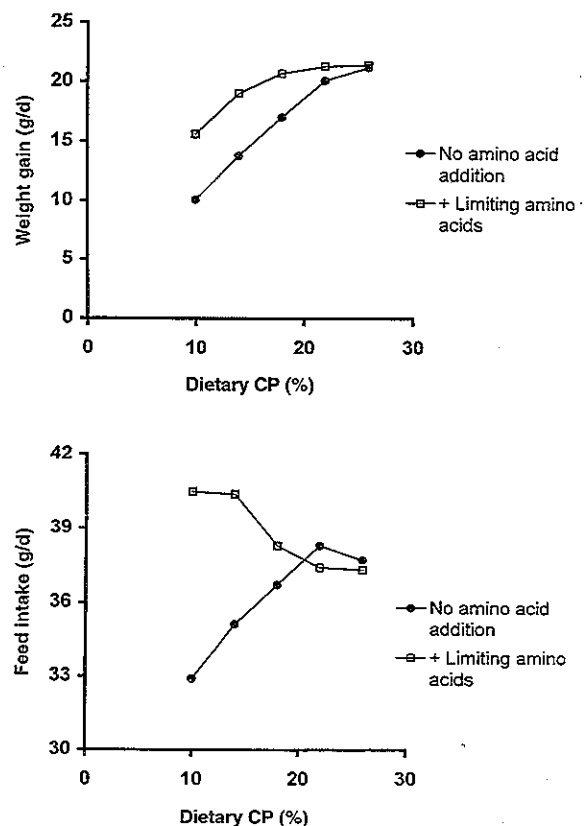

Figure 1. Daily weight gain (top) and daily feed intake (bottom) plotted against dietary CP (%) for chicks fed soybean meal (SBM) that was either unfortified or fortified with methionine, threonine, and valine. Data points are mean values of four pens of four chicks during the period from 8 to 22 d posthatching; pooled SEM values were .40 g/d for weight gain and .7 g/d for feed intake. Data are from Baker and Emmert (1997).
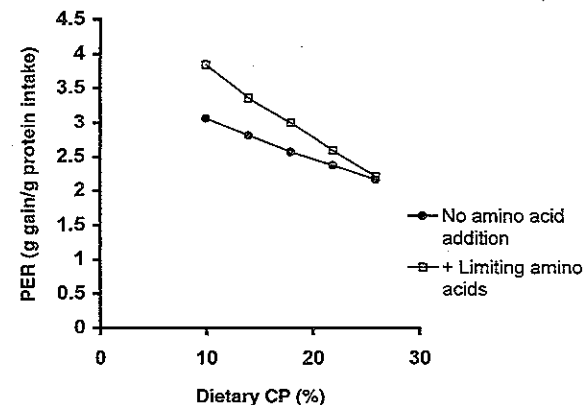

Figure 2. Protein efficiency ratio (PER) of chicks fed graded levels of protein from dehulled soybean meal (SBM) that was either unfortified or fortified with methionine, threonine, and valine. Data points are mean values of four pens of four chicks during the period from 8 to 22 d posthatching; pooled SEM was .05 g/g protein intake. Data are from Baker and Emmert (1997).

1997). At 10% CP in a head-to-head comparison, the PER of unfortified SBM (3.75) was about 25% higher than the PER of unfortified casein (3.01).

In the protein quality studies of Escalona et al. (1986), graded levels of protein from methionine-fortified SBM were fed to young chicks during a 6-d growth trial. The SBM additions in that study were not made isocalorically, and PER values increased between 2.5 and 7.5% CP, after which they decreased markedly from 7.5 to 30% CP. The principal difference between their study and ours (Baker and Emmert, 1997) was in the way SBM was added to the basal diet. In our study involving isocaloric substitution of amino acid-fortified SBM for nonprotein ingredients (dextrose, starch, arenaceous flour), voluntary feed intake increased between 3 and 10% CP but declined thereafter between 10 and 26% CP. In the work by Escalona et al. (1986) involving energy dilution as SBM was incremented, voluntary feed intake increased between 2.5 and 17.5% CP after which it reached a plateau (from 17.5 to 30% CP). It seems likely that the difference between their study and ours in how PER changed as amino acid-fortified SBM was incremented in the lower range of protein intakes is explained by feed intake differences resulting from differences in energy concentrations of the diets.

No intact protein source has an ideal ratio of essential amino acids, and SBM is no exception. Nonetheless, when combined with corn, in particular, corn and SBM diets meet all essential amino acid requirements of pigs and all except SAA requirements for broiler chicks and growing turkeys, which is remarkable. Although the plentiful supply of arginine in SBM represents an excess for pigs,

the high level of arginine is an advantage for poultry because avians cannot synthesize arginine. Excess levels of leucine and total aromatic amino acids (with excess arginine also for pigs) exist in SBM and to an even greater extent in corn and SBM diets, but, relative to other ingredients or grain and oilseed meal combinations, the excess amino acids in SBM are considered minimal.

The future will see genetically modified soybeans that will produce meals that are higher in both protein and key essential amino acids. We have worked with two different high protein SBM samples (one transgenic and one non-transgenic variety) and have found that the amino acids in these varieties are as digestible as those in conventional SBM (Parsons and Zhang, 1997; Edwards et al., 1999). Moreover, relative to conventional SBM, the concentration of lysine was 50% higher in the transgenic variety (with little change in the other amino acids); however, lysine, threonine, valine, and SAA were about 15% higher in the non-transgenic SBM. Not surprisingly, therefore, when fed at a similar concentration (25% of diet), chicks gained faster and more efficiently when fed the experimental non-transgenic SBM than when fed conventional SBM containing 47.5% CP (Table 2).

Protein Quality of Other Soy Products

It has been firmly established in pigs (Berry et al., 1966), rats (Berry et al., 1962), and chicks (Fernandez et al., 1994; Emmert and Baker, 1995) that SBM protein is first-limiting in SAA and second-limiting in threonine. With alcohol-extracted soy concentrates (64% CP) and soy isolates (85% CP), SAA and threonine are also first- and second-limiting, respectively, for chicks (Emmert and Baker, 1995) and rats (Berry et al., 1966). Moreover, protein quality of soy isolates is lower than that of SBM (Maner et al., 1961; Emmert and Baker, 1995),

TABLE 2. Performance of chicks fed two different soybean meals (SBM) at 25% of a semipurified diet[a]

Criterion	Conventional SBM	High protein SBM	SEM
Weight gain, g	144[y]	193[x]	4.8
Protein intake, g	46[y]	67[x]	1.6
Gain:feed, g/kg	372[y]	454[x]	8.7
PER,[b] gain ÷ protein intake	3.13	2.90	.08
Protein accretion, g	19.5[y]	28.2[x]	.08
Protein accretion ÷ protein intake, %	42.4	42.1	.56

[a]Edwards et al. (1999); data represent mean values of four pens of four female chicks fed the experimental diets from d 8 to 20 posthatching. Average initial weight was 94 g.
[b]Protein efficiency ratio.
[x,y]Means within rows with unlike superscript letters are different ($P < .05$).

and "edible" isolates (used for enteral products and infant formulas) are lower in protein quality than are "functional" isolates (used as food additives). This is logical in that both total and digestible levels of SAA and threonine are lower in the protein of soy isolates than in the protein of either SBM or soy protein concentrates (Emmert and Baker, 1995). Rat studies have tended to confirm the superior protein quality of soy flour over that of further processed (and higher protein) soy products (Raskosky, 1970; Bressani, 1975; Liener, 1977). Our work with chicks (Emmert and Baker, 1995) showed that the true digestibility of amino acids was similar between SBM and soy isolates. However, analytically determined SAA and threonine (percentage of protein) were lower in the isolates than in SBM. Apparently, one or more of the extraction and(or) purification procedures removes a portion of a SAA- and threonine-rich protein (or peptide). Edible isolates are prepared by treating functional isolates with H_2O_2 (to reduce bacterial counts), and this, too, decreases analytically determined methionine, cystine, and threonine.

Vitamins and Minerals in Soy Products

Soybean meals and other processed soy products are not complete foods in the sense that they do not furnish the entire array of essential nutrients in amounts that satisfy minimal nutrient requirements. Soybean meal is a rich source of potassium and magnesium, and it also is considered a good source of bioavailable copper and iron. Among the vitamins, SBM is considered to be a rich source of thiamin, niacin, vitamin B6, biotin, choline, and folacin, but, at the levels generally fed, all of the fat-soluble vitamins together with riboflavin, pantothenic acid, and vitamin B12 are deficient in SBM. The macrominerals (calcium, phosphorus, sodium, and chloride) are deficient in SBM, and, because 70% of the phosphorus exists as phytate complexes (Cromwell, 1992), the phosphorus, calcium, zinc, and manganese present in SBM are largely unavailable. Selenium in SBM is not plentiful, and the soil content of selenium in the principal soybean growing areas of the midwestern U.S. is quite low, which contributes to the low concentration of this trace element in most sources of SBM.

Soy protein isolates are often used as protein sources for the study of various mineral and vitamin deficiencies. Work in our laboratory has established that an alcohol-extracted, functional soy protein isolate (85% CP) is completely devoid of bioavailable riboflavin, thiamin, vitamin B6, and choline. It is also much lower in niacin and pantothenic acid than is SBM, but alcohol extraction and the protein isolation procedures employed actually increase the concentration of biotin and folacin. Regarding minerals, the processing of SBM or soy flour to soy protein isolate markedly reduces the concentration of both potassium and magnesium to between 10 (potassium) and 25% (magnesium) of the original values found in SBM. Also, the extraction and purification procedures concentrate

the phytic acid present in soy such that soy isolates and concentrates are actually richer in phytate than SBM (Erdman, 1979).

Toxic Factors

It is well known that raw soybeans contain several toxic factors that must be inactivated prior to consumption by non-ruminant animals. Fortunately, except for the oligosaccharides (primarily stachyose and raffinose), the heat treatment employed in hexane extraction inactivates virtually all of the inhibitors present in soybeans. Liener (1962, 1977, and chapter 2 of this book) has written extensively on the toxic factors present in raw, uncooked soybeans; so, the comments that follow will concentrate on recent feeding studies involving SBM made from genetically modified soybeans that contain far lower quantities of protease (e.g., trypsin) inhibitors, lectins (i.e., hemagglutinins), or oligosaccharides. There are both goitrogenic and estrogenic factors present in soybeans, but heat treatment and solvent extraction are known to remove the goitrogenic activity, and research on the physiological implications of the phytoestrogenic activity of soybean products is still in its infancy.

Osborne and Mendel (1917) were the first to publish that raw uncooked soybeans would not allow rats to grow optimally. Since that time, verification of poor growth in several animal species has been reported when raw soybeans were consumed. Protease inhibitors in soybeans are mainly those that inhibit the pancreatic enzyme trypsin, and both a Kunitz (Kunitz, 1945) and a Bowman-Birk (Bowman, 1944; Birk, 1961) trypsin inhibitor are present in raw soybeans. The pancreatic enzyme chymotrypsin is also inhibited by the Bowman-Birk factor.

Swine and poultry work on uncooked soybeans lacking the Kunitz trypsin inhibitor (Bernard and Hymowitz, 1986) began in the late 1980s (Cook et al., 1988; Han et al., 1991; Zhang et al., 1991; Stickler, 1992; Anderson-Hafermann et al., 1992; Zhang et al., 1993). Performance of animals fed raw Kunitz-free beans was found to be substantially better than performance of animals fed raw conventional soybeans, but, because the Bowman-Birk inhibitor as well as lectins were still present, conventional, dehulled SBM produced better growth responses than raw, Kunitz-free soybeans. Similarly, it was established that the advantage of solvent-extracted SBM over raw, Kunitz-free soybeans was greater in young animals than in older animals.

A lectin-free soybean variety was developed in 1995 at the University of Illinois (Bernard and Nelson, 1996), and the first feeding studies with this new variety were published in 1999 (Douglas et al., 1999). In their report, raw, lectin-free soybeans were compared with raw, Kunitz-free soybeans; dehulled SBM served as a positive control, and raw conventional soybeans served as a negative control. Diets were formulated to be isonitrogenous and isoenergetic. All soybean samples contained roughly the same concentration of the Bowman-Birk (trypsin-
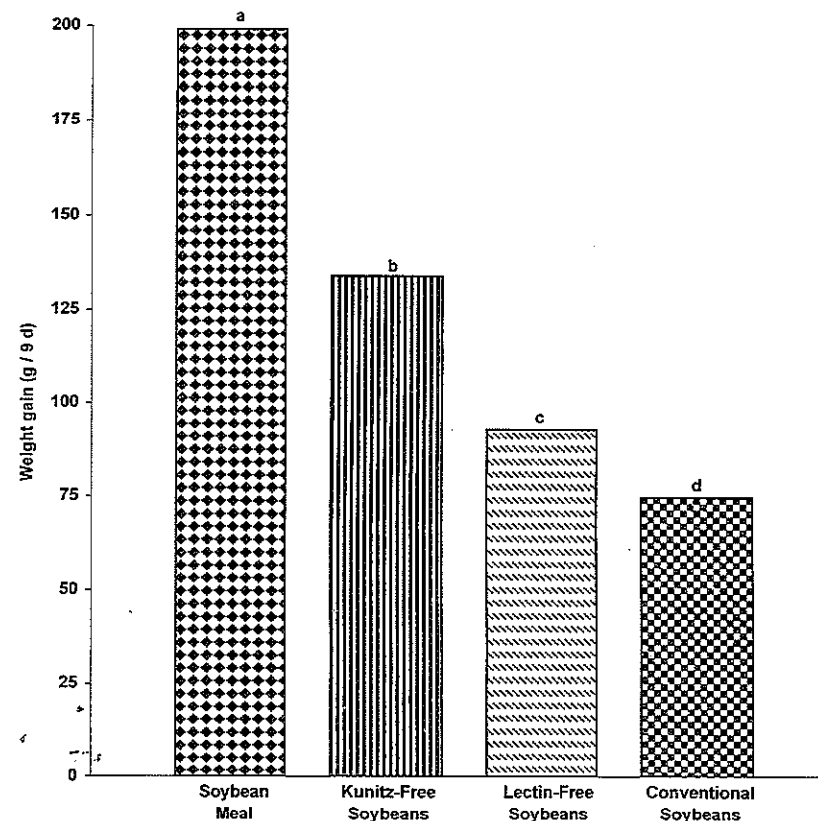

Figure 3. Weight gain (8 to 17 d posthatching) of chicks fed semipurified diets containing 23% CP from soybean meal (45.4% CP), unheated Kunitz-free soybeans (35.7% CP), unheated lectin-free soybeans (35.7% CP), or unheated conventional soybeans. Data are mean values of four pens of six male chicks (pooled SEM = 3 g), and treatment bars with unlike superscript letters indicate differences ($P < .05$). Adapted from Douglas et al. (1999).

chymotrypsin) inhibitor (11 to 13 mg/g DM), but the Kunitz-free sample contained only .04 mg/g DM of the Kunitz trypsin inhibitor; the conventional and lectin-free soybean samples contained 28.4 to 30.0 mg/g DM of this inhibitor. The lectin concentrations (mg/g DM) were 8.3 for the conventional bean, 8.0 for the Kunitz-free bean, and essentially 0 for the lectin-free soybean sample. As shown in Figure 3, chicks fed Kunitz-free soybeans grew faster than those fed lectin-free soybeans, and lectin-free soybeans outperformed conventional raw soybeans. However, the growth rate of birds fed Kunitz-free soybeans was still only 67% of that obtained with dehulled SBM. Therefore, it is likely that the combination of

Bowman-Birk inhibitors, lectins, and oligosacharides in the Kunitz-free soybeans explains the failure of chicks to achieve maximal growth rates. Indeed, Anderson-Hafermann et al. (1992) showed that heat treatment of Kunitz-free soybeans would allow chicks to grow at the same rate as those fed solvent-extracted SBM. They also indicated that less heat was required with Kunitz-free soybeans than with conventional soybeans, and this was viewed as a potential advantage (energy savings) for the Kunitz-free soybean variety.

The oligosaccharide and fiber components of SBM have long been thought to be the primary reasons why poultry (with a short gut and fast digesta passage rate) obtain >20% less metabolizable energy (**ME**) from SBM than that obtained by swine. Because poultry consume well over 50% of the SBM used in animal feeding, this factor probably represents the most serious limitation of SBM usage in animal nutrition. Steggerda (1968) demonstrated that the oligosaccharides in soybeans cause gastrointestinal gas production in rats, dogs, and humans.

Coon et al. (1990) extracted SBM with ethanol to remove a majority of the oligosaccharides and found that the extracted SBM produced true ME values in adult cockerels that were 20% higher than those obtained with unextracted SBM. The extracted SBM also resulted in a slower gut transit time and a higher cecal pH value. Parsons et al. (1996) worked with a genetically modified SBM that was low in oligosaccharides and reported results similar to those of Coon et al. (1990). With pigs and dogs, however, conventional SBM has been shown to be utilized as efficiently for energy production as low oligosaccharide SBM (Zuo et al., 1996; McCalla et al., 1998).

Summary

Soybean meal is the most important oilseed meal used in animal feeding. It is rich in both lysine and tryptophan, and it contains plentiful quantities of potassium, magnesium, copper, iron, and most of the water-soluble B vitamins. Nonetheless, it is deficient in calcium, available phosphorus, sodium, chloride, selenium, zinc, and fat-soluble vitamins. Among these, the deficiency of available phosphorus is most important from an economic standpoint. Most of the undesirable factors in raw soybeans are corrected by heat treatment and solvent extraction, but the fiber and oligosaccharides of SBM are not well utilized for energy by poultry. Because poultry consume >50% of the SBM used in animal feeding, new processing procedures, such as alcohol extraction, or genetic modifications that result in reductions in oligosaccharide content would be of substantial benefit to poultry and would likely expand the market for SBM even further.

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Non-Nutritive Factors and Bioactive Compounds in Soy

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Introduction

The soybean has long been recognized not only as a valuable source of edible oil but also as an excellent source of protein for animals as well as humans. Unlike most proteins, the nutritional value of which is largely determined by amino acid composition, the full nutritional potential of soybean protein is attained only after a certain amount of heat has been applied (Osborne and Mendel, 1917). Implicit in this observation is the realization that, in soybeans, there must be factors that can interfere with the utilization of protein. In addition to those factors that are inactivated by heat, other factors are known to be present that are not fully destroyed by heat and which can similarly detract from the nutritional quality of soybean protein. Table 1 lists the heat-labile and heat-stable antinutitional factors known to be present in soybeans. In some cases, only partial inactivation by heat can occur so that a strict assignment to one or the other of these two categories may be somewhat arbitrary. Each of these factors will be considered with respect to its biochemical properties, nutritional significance, physiological action, and the possible elimination of negative effects by appropriate processing procedures.

Protease Inhibitors

Biochemical Properties

The ability of a soybean extract to inhibit trypsin was first reported in 1938 by Read and Haas. The protein fractions responsible for this inhibition were subsequently partially purified by Bowman (1944) and Birk (1961), and the so-called Kunitz trypsin inhibitor was crystallized (Kunitz, 1945). It is now known that the specificity of these inhibitors is not necessarily restricted to trypsin, but some of these may in fact inhibit chymotrypsin and elastase as well as a number of other so-called serine proteases (proteases in which serine constitutes the