Feedstuffs

A review: 100 years of soybean meal

A historical look at the soybean and its use for animal feed.

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The 50-year historical review of soybean meal (SBM) published in Feedstuffs in 1970 by Dr. J.W. Hayward highlighted many of the pertinent advancements concerned with animal nutrition, product development and promotional aspects of

U.S. SBM. In fact, 1920 marked not only the beginning of the industrial production of soybean oil and SBM in the U.S., but also the year that the American Soybean Assn. was founded (Hymowitz, 1990). The use of SBM at the time this 50-year review was published was gradually increasing worldwide, but it was still in its infancy in many respects.

In the 1920s and 1930s, SBM was unknown to many companies and nutritionists and it was not used extensively in animal feeds. In fact, six U.S. states were not using SBM in feed formulas for poultry. Hayward pointed out in his review how the use of SBM in broiler diets had increased from little or none used in 1930 to 2.5 million tons in 1970. To promote its use in animal nutrition, Hayward and a special committee in 1938 decided to visit nutritionists at the U.S. Department of Agriculture in Beltsville, Md., and several universities and spread the word about SBM. Since that time there has not been any other feed ingredient that has been studied more than SBM. Thousands of scientific articles are credited with increasing our knowledge about this valuable feed ingredient and spreading this knowledge worldwide.

A lot of information about SBM had been acquired during the first 50 years from research conducted in industry as well as in universities in many parts of the world, especially in the U.S. Even though a lot had been learned, much more about the soybeans and its meals still needed to be investigated to keep this source of high-quality plant protein at the forefront and moving forward in both human and animal nutrition. At about the time Hayward published his review there were three areas that began to clearly emerge as being important for proper utilization of SBM when animal feeding is the objective. Today, these three areas of research still dominate most of the worldwide research concerns with SBM. These three areas are (1) amino acid digestibility (2) anti-nutritional factors (ANF) and (3) metabolizable and net energy (ME and NE, respectively). Considering SBM in the worldwide arena, these three factors are precisely what makes SBM so attractive. Compared to other protein sources, SBM has consistently been shown to contain less nutrient variability and lower concentrations of anti-nutritional factors, and higher amino acid digestibility and metabolizable energy. Even though it is common knowledge today that these three areas must be considered in determining the success of SBM in animal feeding, Hayward's review mentioned only energy because of the work that had been conducted at Cornell University with metabolizable energy for poultry in the early 1960s, which included SBM and other soy products.

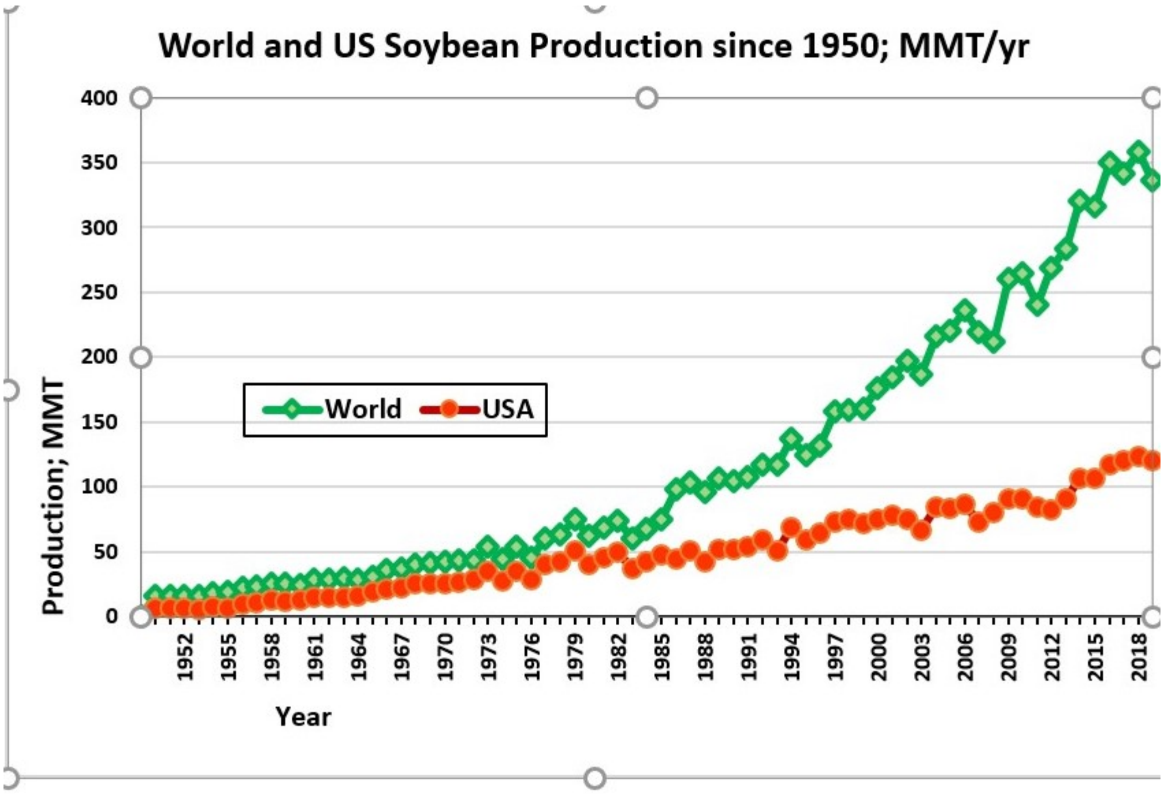
The objective of this review is to follow Hayward's steps and to briefly summarize the main nutritional highlights of the last 50 years of SBM as an animal feed ingredient and the implications of its utilization. Certainly, this is a limited review but hopefully we encourage other colleagues particularly in the areas of processing, engineering and marketing to tell us the story.

Production of soybeans and SBM worldwide

Although soybeans were introduced in the U.S as early as 1766 (Hymowitz, 1990), it was in the early 20th century, that their production - and that of its main by-product soybean meal - has increased steadily (Fig. 1). Recent levels of production for soybeans and SBM are provided in Table 1. These values, set against a world-wide production of approximately 1.1 x 10^9 MT of compound feed (Alltech, 2019), emphasize the key role of SBM in modern compound feed production.

The consistent increase in SBM production and utilization reflect on one hand the parallel increase with livestock production (most notably poultry and swine) and on the other hand, the superior nutritional value (price: quality relationship) for SBM relative to other protein sources.

Figure 1. World-wide and US soybean production.



Source: Schaub, J., et al., 1988 - The U.S. Soybean Industry, Commodity Economics; Division, Economic Research Service, USDA. Agricultural; Economic Report No. 588. ASA – The American Soybean

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Table 1. Production of soybeans and SBM world-wide; MMT.

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	2015/16	2016/17	2017/18	2018/19	Aug. 2019/20	Sep. 2019/20
Soybeans	316.6	350.5	341.6	362.1	341.8	314.4
Soybean meal	216.0	225.9	232.4	234.8	240.6	240.0

https://www.usda.gov/oce/commodity/wasde/

World Agricultural Supply and Demand Estimates; USDA, 2019.

Amino acid digestibility: poultry

The beginning of a quantitative systematic approach to animal nutrition is the landmark work of Henneberg and Stohman in 1860 in which they delivered for the first time proximate analysis. The next logical step was the measurement of the digestibility of the components of the proximate analysis of the feed which started around year 1900 when Wilbur Atwater working at the Connecticut Experiment Station published equations and procedures for determining digestible and metabolizable energy in feed ingredients (Carpenter, 1994). As Ewing (1963) said, the analyses of feeds are of great importance, but still the digestibility of the feed by the animal is of greater importance for practical purposes. In fact, by 1938 Crampton and Maynard had already developed their method for cellulose digestibility and had also found that the Weende´s concepts of crude fiber and N-free extract didn't fit very well for ruminants. However, by 1970 when Hayward published his paper on SBM no mention of digestibility accomplishments was made in his section listing 12 "nutritional highlights". At least one of the reasons for that is because the generation of digestibility coefficients in experiments with different animal species is time consuming and expensive. It is only in the last 50 years that a considerable amount of digestibility data have been produced, specifically for SBM. Sibbald proposed first his true metabolizable energy assay for poultry feedingstuffs in 1976, and later (1979) this author proposed the extension of the concept to determine what today most people in the industry call digestible amino acids. Parsons et al. (1981) further standardized the procedure working with dehulled SBM. The current standardized procedure also known as the precision-fed rooster assay (Corray et al., 2018) is performed with conventional roosters for the determination of TMEn, and with cecectomized roosters for standardized amino acid digestibility. Similar work was conducted at other laboratories such as Rhône-Poulenc Animal Nutrition (1993) in France. Because the basics of the Sibbald methodology are assay brevity, linearity of input/output, and additivity of values with a collateral of being less expensive, this methodology is partially responsible for the literally hundreds of coefficients of digestibility of amino acids published and available today for SBM and for most of the relevant raw materials for poultry nutrition.

Over the past 50-60 years SBM has become the reference ingredient for feed evaluation, notably protein ingredients. However, to maximize nutritional value SBM – more than any other ingredient – relies on accurate heat processing, avoiding under and overprocessing. Overprocessing results in decreased digestibility for lysine, arginine, and cysteine (Parsons, 2000). Amino acid digestibility determination on samples of representative lots of industrially over-processed SBM is key for the understanding and formulation of SBM within the concept of precision nutrition (Sifri, 1997). Parsons et al. (1992) working with a laboratory model of overprocessing (autoclaving) demonstrated the negative effect autoclaving had on analyzed lysine concentrations suggesting that substantial quantities of advanced Maillard reaction products are formed during overprocessing at the expense of intact amino acids. Presumably, a similar damage occurs under industrial SBM overprocessing during the solvent-extraction process judging by the performance results reported by Lee at al. (1991) with turkeys fed SBM custom over-processed at a commercial oilseed processing plant in North Carolina.

Directly associated with overprocessing of SBM was the work by Araba and Dale (1990) demonstrating that an *in vitro* technique, the solubility of SBM protein in KOH was correlated with *in vivo* performance of poultry enabling nutritionists and formulators in the industry anticipation to deal with the variability of commercial SBM quality. These observations which were corroborated by independent laboratories (Parsons et al., 1991; Lee et al., 1991) closed the cycle for the quantitative assessment of SBM quality: On one hand, trypsin inhibitors, as discussed elsewhere in this paper correlates with underprocessing, on the other hand, protein solubility in KOH correlates with overprocessing. Certainly, the industry has come a long way, particularly the US soy processing industry, in terms of understanding protein quality. According to Hayward (1975), in the 1950 report by the Soybean Research Council on a survey in which a total of 53 samples (28 expeller SBMs and 25 solvent extracted) were evaluated from 40 participating brands, 87% of the expeller meals and 28% of the solvent extracted were overprocessed. In contrast, Sotak-Peper and co-workers (2015) demonstrated that of 22 samples of SBM collected from United States processors, none were underprocessed and none were overprocessed.

Heat-labile antinutritional factors

Although Osborne and Mendel (1917) discovered that heat treatment was necessary to improve the nutritional value of soybeans to be used as food, the exact reason behind that need was not obvious. In fact, it was not until 1945 that Kunitz crystallized for the first time a trypsin inhibitor from soybeans (Kunitz trypsin inhibitor). A second protease inhibitor also present in soybeans was partially crystallized by Bowman in 1944, and better defined in 1961 by Birk, therefore the Bowman-Birk inhibitor was solidly established in 1961. Each of these protease inhibitors displays a number of electrophoretic forms or variants (Hwang et al., 1977; Kim et al., 1985). Therefore, today the term "trypsin inhibitors" in soybeans includes several variants of Kunitz and Bowman-Birk inhibitors with antitrypsin and anti-chymotrypsin activity. However, because the mechanism of the inhibition was not clearly understood by the 1950's, the actual role of the inhibitors in retarding of growth of poultry and swine was still debated. For instance, Borchers (1958) agreed with Liener (1958) that there was good evidence that the growth-retarding effect of raw SBM on rats and mice was not due to anti-tryptic activity. Rather, they thought it was lower amino acid digestibility, particularly methionine in raw soybeans due to a specific interference with the enzymatic release of methionine. But Almquist and Merritt (1953) had a different interpretation of the experimental data and concluded that trypsin inhibitors were indeed responsible, not only for a methionine deficiency caused by feeding 20% raw SBM to chicks, but also for the accentuated deficiency of tryptophan in the case of a chick diet marginal in this amino acid. These authors reported similar observations for lysine, arginine, and isoleucine. It is currently accepted that pancreatic secretion is controlled by a negative feedback mechanism by which the secretory activity of the pancreas is regulated by the level of trypsin in the small intestine (Green and Lyman, 1972). Consequently, as the level of trypsin in the duodenum is reduced due to formation of the trypsin inhibitor – trypsin complex, the pancreas is stimulated to produce more enzyme in order to compensate for the loss. This trypsin inhibitor – trypsin complex is the reason for the growth depression induced by the trypsin inhibitor because trypsin cannot effectively hydrolyze dietary protein, resulting in a N exogenous loss, and also in an endogenous loss of amino acids because trypsin is lost in the excreta (Schulze, 1994;

Grala et al., 1998; Liener, 2000). In chickens, mice and rats, excess trypsin inhibitor intake results in the pancreas producing more trypsin, which in turn leads to pancreatic hypertrophy (Chernick et al., 1948; Miles and Featherston, 1976; Yanatori and Fujita, 1976). However, this is not always the case in swine (Schulze, 1994) although high trypsin inhibitor concentrations results in dramatically reduced amino acid digestibility in pigs (Yen et al., 1974; Schulze, 1994; Goebel and Stein, 2011a).

Lectins (previously called hemagglutinins) are the second most abundant heat-labile anti-nutritional factors in soybeans (Liener, 2000). The soybean lectin was first reported by Liener in 1953. The discovery of lectin-free cultivars of soybeans (Pull et al., 1978) along with a similar discovery of a variant free of the Kunitz trypsin inhibitor (Bernard and Hymowitz, 1986), provided a unique opportunity to compare the relative contribution of these two anti-nutritional factors against conventional raw soybeans (Douglas et al., 1999). Chicks fed a diet containing raw Kunitz-free soybeans had better growth than those fed a diet containing raw lectin-free soybeans when both were compared with conventional raw soybeans. These results indicate that the Kunitz trypsin inhibitor is a more important anti-nutritional factor than are the lectins (Liener, 2000). If the ever-present Bowman-Birk inhibitor is also taken into account, then it is clear that trypsin inhibitors are the most relevant of the heat-labile anti-nutritional factors in soybeans.

Since the 1990s the poultry industry (particularly outside the United States) has faced a syndrome called the "rapid feed passage syndrome" which is correlated with residual trypsin inhibitor content of specific lots of commercial SBM (Ruiz and Belalcázar, 2005). Rapid feed passage ("transito rapido" in both Spanish and Portuguese) is defined as the condition in which broiler droppings lose their normal shape and consistency, do not display the characteristic white uric acid cover, contain undigested feed that is visible to the naked eye, usually have a yellowish-orange color, are frequently watery and contain reddish sloughed intestinal tissue. Broilers in a flock experiencing a rapid feed passage outbreak have dirty feathers, lack body weight uniformity and display poor pigmentation. As a consequence, the litter becomes wet and slippery, foot pad lesions often develop, feed conversion is negatively affected, body weights are lower than the desired standard and considerable economic losses may be realized (Ruiz and Belalcázar, 2005; Ruiz 2012a).

This brings a new discussion into the role of residual anti-nutritional factors in SBM, specifically trypsin inhibitors. Because the important question is what is the maximum residual heat-labile anti-nutritional factors in commercial SBM (and other soy products such as full-fat soybeans) that is tolerable to animals. Historically, the issue of "adequacy" was settled at the end of the 1940s with the measurement of an indirect analyte, urease activity (Caskey and Knapp, 1944; Bird et al, 1947) with the range of adequacy established between 0.05-0.20 pH units or delta pH. A urease value above 0.20 indicated SBM was underprocessed (insufficient heat treatment) although an acceptable delta pH value of 0.30 was also suggested (Hayward, 1975). In contrast, a delta pH value below 0.05 indicated that SBM was likely overcooked. Despite the fact that a high correlation exists between trypsin inhibitors and urease activity in solvent-extracted SBM (Mustakas et al., 1981; Ruiz, 2012b) the actual measurement of residual trypsin inhibitors in the industry does not often occur. In other words, urease activity became "the test". An absolute, when in reality it was just an indirect measurement of heat-labile antinutritional factors, specifically for trypsin inhibitors. Because rapid feed passage outbreaks may occur in broiler chickens in different geographies with feeds containing 25-30% SBM whose urease activity is well within the range of "adequacy", it becomes imperative to reinterpret the range of adequacy and to connect it to actual measurements of trypsin inhibitors in SBM. Ruiz (2012b) has suggested a new range of adequacy for urease activity of 0.000 - 0.050 delta pH which correlates with approximately 1.65 - 2.35 mg of trypsin inhibitors per gram (3.0-4.0 TIU/mg) of SBM.

Alcohol-extracted soybean meal and nutritional implications of oligosaccharides in poultry

Soybean meal, just as any other natural feed ingredient, serves only as a “vehicle” responsible for carrying nutrients and energy into an animal’s diet. Since energy and protein are the two most costly components of an animal’s diet, respectively, it is easy to understand why the three previously mentioned areas of research with SBM have been investigated intensively through the years and continue to be the focus of researchers. The chemical composition of SBM, especially the carbohydrate composition, anti-nutritive factors and protein/amino acids are known to be influenced by several factors such as geographical origin, genotype, soybean processing and the environmental and agronomic conditions under which the soybeans are grown (Parsons et al., 2000; Grieshop and Fahey, 2001; Grieshop et al., 2003; Karr-Lilienthal et al. 2005; Goldflus et al., 2006; Thakur and Hurburgh, 2007; Frikha et al., 2012). Excellent discussions of the anti-nutritional and toxic factors present in soybean products can be found in the publications of Liener and Kakade (1969), Liener (1981, 1994), Balloun (1980), Wright (1981), Hsiao et al. (2006), Choct et al. (2010), and Dourado et al., (2011).

Comprehensive reviews by Kar-Lilienthal et al. (2005), Choct et al. (2010) and Choct (2015) provide a detailed discussion of the composition and chemical structures of the anti-nutritional carbohydrates. Despite the nutritional knowledge gained since the 50-year review of the use of SBM in animal feeding was published (Hayward, 1970) the carbohydrate composition remains the least understood constituent in SBM (Choct et al., 2010) and continued research in this area is needed. As referenced by Choct et al., (2010), following solvent extraction from the soybean, the meal contains approximately 48% crude protein, 35-40% carbohydrates, 10-12% water, 5-6% minerals and 1-1.5% lipids. Of the 35-40% carbohydrates present, the majority consists of non-starch polysaccharides (NSP) and free sugars such as the mono-, di-and oligosaccharides with starch present at less than 1% (Choct, 1997; Cervantes-Pahm and Stein, 2010).

The soluble NSP and the oligosaccharides (mostly raffinose and stachyose) have been studied extensively because they contribute to the gross energy component of SBM but cannot be utilized directly as a source of calories by monogastric animals. Because there is no endogenous enzyme (alpha-galactosidase) that can hydrolyze the glycosidic bonds between the monosaccharides in oligosaccharides and NSP they remain in the digesta entering the hind gut where they may eventually be fermented by the microbes. As pointed out by Barzegar et al., (2019), a major reason SBM has a lower apparent metabolizable energy content in poultry than corn and wheat is due to the presence of poorly digested NSPs and the oligosaccharides. The metabolizable energy value of SBM is listed as being higher for swine (NRC, 1979, 1998, 2012) than for poultry (NRC, 1984, 1994) (McGinnis, 1983; Perryman and Dozier, 2012). Coon et al. (1988, 1990) presented an explanation of why the metabolizable energy of dehulled solvent extracted 48.5% protein SBM was 1,045 Kcal/Kg higher for swine than poultry. Due to the anatomical differences in the lower digestive tract, species differences exist in the physiology of digestion with swine having more capacity and a better opportunity due to a longer digesta transit time (Choct et al., 2010) to ferment the NSPs and oligosaccharides in SBM.

The SBM oligosaccharides have been extensively studied with regards to their nutritional implications and have been reported to promote positive as well as negative effects (Chow, 2002; Karr-Lilienthal et al., 2005; Jankowski, et al., 2009; Choct et al., 2010; Faber et al., 2012). Positive effects have been related to promoting and maintaining populations of beneficial bacteria by serving as a prebiotic. It is these bacteria and their products of fermentation that are related to promoting intestinal development, proper gut and immune function and a healthy digestive tract overall. As mentioned by Choct et al., (2010), it must not be forgotten that elevated levels of oligosaccharides in poultry diets have been reported to increase fluid retention, hydrogen production, and diarrhea leading to impaired nutrient utilization, wet droppings and leg disorders. Also, the overall effect of oligosaccharides is related to the sources, type and dietary concentrations.

During the heat processing of SBM only the heat labile anti-nutritional components are inactivated. Therefore, SBM contains soy antigens, phytate, small amounts of insoluble fiber, soluble NSPs and the oligosaccharides (Liener, 2000; Choct et al., 2010). This limits the use of SBM in diets of young poultry and swine as discussed in detail by Stein et al., (2008) and Nahashon and Kilonzo-Nthenge (2011). Improving the utilization of phytate phosphorus in SBM by addition of supplemental phytase to the diet has been studied extensively in poultry as discussed in the publication of Denbow et al., (1995). Since the oligosaccharides are not able to be enzymatically attacked in poultry and swine due to the lack of an endogenous alpha-galactosidase their presence results in a dilution effect and minimizes the amount of metabolizable energy able to be derived from the meal. Therefore, removal of the oligosaccharides would result in a higher protein SBM product that would also have a higher metabolizable energy value.

Today, oligosaccharide removal is common practice with alcohol (ethanol) extraction thanks to the initial research conducted by Dr. Craig Coon and his research team at the University of Minnesota and first reported at a Symposium for Alternative Crops & Products at the University of Minnesota in February 1988 (Coon et al., 1988) and again at the Poultry Science Association meeting in Baton Rouge, Louisiana (USA) that same year. Following publication of this research (Coon et al., 1990) a series of other publications by these investigators arising from research conducted with oligosaccharide-free SBM revealed more about the effect of alcohol extraction on poultry performance (Leske et al., 1991; Leske et al., 1993ab; Leske et al., 1995; Leske and Coon, 1999ab). The research discussed by the Minnesota group in these publications provided some of the earliest data indicating that 1) the removal of oligosaccharides from SBM by alcohol extraction slows down the rate of digesta passage allowing more time for digestion resulting in an improvement in hemicellulose digestion and the digestibility of nutrients, 2) the oligosaccharides are not utilized in the area of the small intestine but are utilized extensively in the area posterior to the ileum, 3) the addition of pure oligosaccharides, originally removed from conventional SBM, back to alcohol extracted SBM (oligosaccharide-free) resulted in TMEn and PER values being reduced back to that of the conventional SBM, 4) the amino acid availability of the oligosaccharide-free SBM is improved by 3 percentage points over conventional SBM and is a plausible reason explaining the higher PER value and 5) a dose response gradient for effects of raffinose and stachyose on TMEn provided evidence that stachyose with its 2 galactose units is more detrimental than raffinose which contains only one galactose unit and if substantial improvement in nutrient utilization is to be expected, at least 80 to 90% of the oligosaccharides should be removed from conventional SBM.

Alcohol extraction of conventional SBM results in a product referred to as soy protein concentrate which contains at least 65% crude protein (DM basis), but still contains substantial amounts of insoluble fiber. Through further processing, the insoluble fiber portion can be removed resulting in a product known as soy protein isolate containing at least 90% crude protein on a dry matter basis. Soy protein concentrate and isolate have been fed to swine and poultry with good results (Cervantes-Pahm and Stein, 2008; Oliveira and Stein, 2016; Batal and Parsons, 2003), but soy protein isolate is usually too expensive to be used in practical production of pigs and poultry. In contrast, there are a number of soy protein concentrates on the market and many of these are included in diets fed to young pigs. Other means of removing the nutrient and metabolizable energy diluting factors in SBM are through enzymatic treatment using a blend of enzymes in order to decrease the concentrations of oligosaccharides and allergenic proteins (Stein et al., 2013). Producing a fermented SBM by treating conventional SBM with a mold (e.g. *Aspergillus oryzae)* or bacteria (e.g. lactobacillus, Bacillus, etc.) is also another effective method of eliminating the oligosaccharides and antigens (Cervantes-Pahm and Stein, 2010). Later in this review these methods of SBM treatment will be discussed in more detail as related to swine. As pointed out by Waldroup and Smith (2018), plant breeders have made exceptional progress on improving yield and better disease resistance in soybeans and in the future more focus will be on improving the nutritive value of soybeans. Since these authors stated it is unlikely that the soybean processing industry in the decades ahead will make extreme changes in its processing procedures, breeding programs focused on lowering the oligosaccharide concentrations in soybeans will be the most desirable route. Of course, in the future, the use by the animal industry of these lower anti-nutritional, higher protein, higher metabolizable energy products derived from conventional SBM will depend on their composition, availability and cost.

How research during the last 50 years has increased our understanding of the nutritional value of SBM fed to pigs

Research with SBM fed to pigs over the last 50 years has primarily focused on the following areas: (1) Measurements of the ileal digestibility of amino acids in SBM. (2) Determination of the energy value of SBM. (3) Determination of the digestible phosphorus value of SBM. (4) Growth performance of pigs fed diets based on SBM, and (5) Developments of soy products that may be fed to young pigs. An understanding of these areas has not only benefited the swine industry, it has also assisted in an understanding of the feeding of SBM to other animals.

Amino acid digestibility

Procedures to determine the ileal digestibility of amino acids (AA) in pigs were developed in the early 1970's (Easter and Tanksley, 1973; Furuya et al., 1974). During the following decades several procedures were used, but by the turn of the century, most laboratories in the world used the so-called "T-cannula" procedure, or modifications to this procedure, that was first described by Furyua et al. (1974). The procedure can be used in weanling pigs, in growing-finishing pigs, and in sows and values for the apparent ileal digestibility of AA were published for a number of feed ingredients including SBM. However, in the 1990's it became clear that values for apparent ileal digestibility obtained in individual feed ingredients were not always additive in mixed diets and the concept of calculating standardized ileal digestibility (SID) was introduced (Stein et al., 2001; 2005). Subsequently, SID values for AA in SB products have been published from a large number of experiments and it has generally been demonstrated that SID of AA in SBM is greater than in most other plant proteins (Gonzalez-Vega and Stein, 2012; Berrocoso et al., 2015; Liu et al., 2016). It was also demonstrated that the SID of some AA in SBM from the United States is greater than in SBM produced from soybeans grown in some other countries (Lagos and Stein, 2017). However the SID of AA in SBM produced in different areas of the United States does not differ (Sotak-Peper et al., 2017), which may be a result of the fact that the soybean crushing industry in the United States usually does a good job of avoiding under-processing and over-processing of the meals.

Thus, the major achievements during the last 50 years in terms of understanding the AA value of SBM was the development of a procedure to determine ileal digestibility of individual AA, understanding of the concept of using SID AA in diet formulation, and realization that the SID of AA in SBM is greater than the SID of AA in most other plant proteins. Combined, these developments have led to SBM being the gold standard in terms of providing AA in diets used in the global feed industry.

Energy value of SBM

The energy value of SBM can be expressed as the concentration of digestible energy (DE), metabolizable energy (ME), or the net energy (NE). Values for DE and ME are determined as described by Atwater more than 100 years ago (Carpenter, 1994). That means that DE values are determined by subtracting fecal energy from gross energy, and ME values are determined by subtracting energy in both feces and urine from gross energy. Values for DE and ME in many different sources of SBM have been published in recent years (Li et al., 2015; Sotak-Peper et al., 2015; Oliveira and Stein, 2016). Whereas it was thought for many years that DE and ME in SBM was less than in corn, it is now well established that values for DE and ME in dehulled toasted SBM are not different from values in corn (Sotak-Peper et al., 2015).

However, it has been known for more than a century that the heat increment associated with digestion and fermentation of diets differ among feed ingredients and values for NE are therefore often used in diet formulation. In the 1970s and 1980s, systems based on NE values for feed ingredients fed to pigs were developed in several European countries, and a classical paper to determine NE values in diets fed to pigs was published in 1994 (Noblet et al., 1994). Most NE values in the industry have been calculated based on the prediction equations published in this paper. These equations add a large negative value on crude protein in ingredients because it is assumed that crude protein provides a limited energy value to the animal. The NE of SBM calculated using this system is, therefore, only 78% of the NE in corn. However, recent research has questioned this approach and newer data indicate that the NE of SBM may be close to the value in corn (Cemin et al., 2019; Munoz, 2019). Because energy is the economically most important component in the diet, this topic is very important and more research in this area will be required in order to determine the exact NE value of SBM.

Determination of the digestible phosphorus value of SBM

The importance of determining P-digestibility in feed ingredients was recognized in the 1980'es and systems for determining apparent total tract digestibility of P were developed (Jongbloed, 1987; Kemme et al., 1997). However, it was later realized that to obtain digestibility values that are additive in mixed diets, a correction for the endogenous losses of P is required and a system based on the standardized total tract digestibility (STTD) of P was introduced (Almeida and Stein, 2010). This system is now recommended and used in North America (NRC, 2012), Brazil, (Rostagno et al., 2011), and several countries in Asia. Values for the STTD of P in most feed ingredients used in diets for pigs have been published in the last decade. Most P in SBM is bound in phytate as is the case for most other feed ingredients of plant origin and only around one third of P in SBM is not bound to phytate (Rojas and Stein, 2012; Sotak-Peper et al., 2016). It has been believed that because pigs do not secrete endogenous phytase, the phytate bound P cannot be digested. However, it is now recognized that pigs do digest a small part of the phytate bound P and STTD values for P in SBM between 40 and 60% have been reported (Rodriguez et al., 2013; Sotak-Peper et al., 2016; She et al., 2017). However, because of the phytate bound P in SBM, the STTD can be increased if microbial phytase is added to the diets, and STTD values in SBM in diets containing microbial phytase is often between 70 and 80% (Sotak-Peper et al., 2016).

Growth performance of pigs fed diets based on SBM

Diets that are balanced in all indispensable AA are easily formulated based on cereal grains and SBM. However, alternative protein sources such as canola meal, distillers dried grains with solubles, field peas, or rice bran may also be used to supply the needed AA in the diets. A large number of experiments have been conducted specifically in the last two decades to determine growth performance of pigs fed diets containing alternative proteins rather than SBM. The standard for assessment of alternative proteins, therefore, often is that the protein needs to support the same growth performance as diets based on SBM. So again, SBM clearly is considered the gold standard for AA supply in diets for pigs. However, whereas there have been reports of other protein sources being able to partially or fully replace SBM without negatively impacting growth performance of growing-finishing pigs (Stein et al., 2006; Widmer et al., 2008; Little et al., 2015; Parr et al., 2015; Overholt et al., 2016; Casas et al., 2018), there are no other protein sources that have been proven to be better than SBM. The reasons for these observations are related to the excellent AA balance and digestibility in SBM, but the success of SBM as a source of AA in diets for pigs likely is also a result of the low fiber concentration and the general lack of variability among sources of SBM.

Developments of soy products that may be fed to young pigs

It has been long recognized that young pigs generally do not tolerate large quantities of SBM in their diets, which may be a result of the oligosaccharides in SBM as well as other anti-nutritional factors. However, during the last three to four decades, a number of specialized soybean products have been developed and common for these products is that they have very low concentrations of oligosaccharides. As mentioned earlier, oligosaccharides may be removed via alcohol extraction, which also removes other soluble carbohydrates, and results in production of soy protein concentrate (Lusas and Rhee, 1995; Endres, 2001). In the United States, a product can only be sold as soy protein concentrate if it contains 65% crude protein on a DM basis. There are a number of soy protein concentrates on the market, and in general, the SID of AA, the DE and ME, and the STTD of P is either similar to SBM or greater (Cervantes-Pahm and Stein, 2008; Navarro et al., 2017; Oliveira and Stein, 2016; Casas et al., 2017). A different way of removing oligosaccharides from SBM is to ferment or enzyme treat the meals after SBM has been produced. These technologies are widely used and a number of commercial products are currently being marketed throughout the world. Enzyme treated or fermented soybean products contain no oligosaccharides, and all sucrose is also removed, and the concentration of trypsin inhibitors is sometimes also reduced. The digestibility of AA and energy in enzyme treated or fermented SBM is usually close to that in regular soybean meal, although ME values are sometimes slightly reduced due to the elimination of sucrose (Rojas and Stein, 2013). However, because much of the phytate bound P is released during fermentation or enzyme treatment, the digestibility of P is greater in fermented or enzyme treated SBM than in conventional SBM (Goebel and Stein, 2011b; Rojas and Stein, 2013).

The main objective of developing soy protein concentrate or fermented or enzyme treated SBM is to use these products as replacements for animal proteins, that are typically added to diets for young pigs. Indeed, in a number of experiments, it has been demonstrated that these added value soy products may replace animal proteins in weanling pig diets without negatively impacting growth performance (Kim et al., 2010; Jones et al., 2010; Rojas and Stein, 2015; Casas et al., 2017). It is therefore likely that more work will be conducted in this area in the future.

The role of soybean meal in ruminant nutrition.

The inclusion of SBM in ruminant diets is lower than that in monogastric diets. Of the total US SBM usage approximately 9.0 % is used in dairy diets and a much smaller proportions in beef (0.8 %) and small ruminant diets (0.1 %) (DIS, 2018). At 2018/2019 soybean production levels and dairy cow numbers (USDA, 2019), this suggest an average use of around 650 kg SBM/cow/yr or approximately 8.0 % of the dairy ration in the US. In countries that do not produce soybeans, the SBM inclusion level is lower due to a more important use of other protein sources such as sunflower, rapeseed (Canola) among others. Nevertheless, under many practical and research situations, SBM – used as either an ingredient or supplement - is considered “the reference” for protein ingredients. This position has been gradually achieved in the first part of the 20th century (covered by Hayward’s review) and solidly confirmed over the past 50 years. SBM palatability, energy content, amino acid profile and rumen-degradation characteristics make it an excellent, competitive and widely available protein source for ruminants.

SBM, originally referred to as soybean cakes, was used for the fattening of cattle in China well before the 20th century (Shurtleff and Aoyagi, 2016). The first literature references to SBM as a protein source in ruminant diets in Western countries dates back to the early 1900s with a series of reports by Lindsey (1904); Lindsey et al. (1909) from the Massachusetts Agricultural Experiment Station. In the first studies Lindsey (1904) evaluated soybean meal (originally defined as “ground soybean seeds”) in digestibility trials with sheep. This was followed by several other studies terminating with a study evaluating the effect of “soybean cake” and soy bean oil on milk quality. Interest in Europe paralleled these developments and shortly after Lindsey's work in dairy cows, Hansson (1910) – referring to a 1909 Swedish study – reported in a German publication on the value of soybean cake or soybean meal for "milch cows". These first nutritional evaluations of soy products in ruminant diets follow the importation and spread of soybean in the United States and Western European countries from China.

The original use of SBM in ruminant rations was primarily as a top-feed or supplement to forage rations (grazed or stall-fed) in which SBM was generally mixed with grains. The level of SBM feeding was originally based on fixed ratios between SBM and grain (1:4) providing a roughly balanced concentrate (20 % crude protein) supplement to forage diets. The ensuing recognition of the benefit of more balanced - and thus formulated - diets led to additional research of the nutritional composition of SBM for dairy and beef animals. Interest and subsequent research went crescendo after the early "rudimentary" evaluations. The Journal of Dairy Science (JDS) saw publications with "soybean meal" evaluation as the main objective increase steadily. Since 1910 - the first issues of the JDS - there have been 1277 articles with "Soybean meal" in the Title, the Abstract or among the Keywords. The fist article on SBM in the JDS appeared in 1922 entitled: "Coconut Meal, Gluten Feed, Peanut Meal and Soybean Meal as Protein Supplements for Dairy Cows" (McCandlish and Weaver, 1922) suggested that SBM was approximately of similar value to the other protein ingredients. Subsequent research publications changed that opinion and determined the relative advantageous use of SBM for ruminants.

In the Journal of Animal Science (JAS) a total of 329 research articles on SBM have been published in the Ruminant nutrition section since 1967 (publication of the first article referring to "Soybean meal" or "SBM"). Nine articles on SBM for ruminants were published in the JAS between 1967 and 1970. With increasing numbers afterwards (72, 91, 96 and 40, respectively in each subsequent 10-year period).

Nutrient composition of "soybean oil meal" was included in the earliest Dairy and Beef NRC tables (1950 onwards) under the heading of "Concentrate composition". In the first published tables the emphasis was on mechanical extracted SBM with 41, 43 and 44% crude protein with values provided for digestible crude protein (no Crude Protein) and TDN and only a very limited number of additional nutrient specifications. Subsequent editions of Dairy and Beef NRC tables followed the general processing and production tendency to switch from mechanically extracted SBM to solvent extracted SBM, and expanded on the nutrient description. Table composition of SBM in terms of crude protein and TDN differed considerable (3 – 10 %) between editions reflecting the increase in the database and the composition (as well as changing committee members and their opinions presented in the different editions). Similar evolutions over time can be found in other international tables. In all of these feeding tables and nutritional guidelines for ruminants, references to anti-nutritional factors (ANF) are limited. This is in part due to the relatively low sensitivity of growing and mature ruminants primarily due to the "neutralizing effect" of the rumen on ANF. Only in pre-ruminant calves residual ANF from soy products may exert a negative effect (Lalles et al., 1996).

The changes over time in ruminant nutrient values for SBM in the different feedstuff tables reflects progress in a more precise description of nutrient characteristics of feed ingredients and the requirements of the animal. The TDN system was replaced by the more precise net energy system and Crude Protein by a more detailed description of the protein fraction (down to its non-protein N and amino acid composition) and its fate in the rumen or post-ruminally. The associated system changes that came about at the beginning of the 1990's led to a re-evaluation of the potential of SBM. The more precise and higher nutrient density of SBM, especially in terms of energy and amino acids, relative to other protein ingredients had an undeniable positive effect on the increase in SBM utilization in ruminant diets. The different forms of SBM, notably expeller versus solvent extracted SBM (e.g. Broderick et al., 1990) and rumen protected soy products were re-visited or developed (Santos et al., 1998) and added to the increase in use of SBM. Practical results confirmed what a large number of research trials had shown namely that expeller or heat treated SBM (or additional types of treatment to improve rumen by-pass protein from SBM) can play a key role in improving animal performance and reducing N-load/excretion associated with normal solvent extracted SBM or alternative ingredients.

From the early nutrient descriptions and simple formulation packages to the more recent models (empirical or mechanistic) estimating supply of metabolizable AAs, SBM in its many types and specifications has played an important role in establishing rations for dairy and meat animals; especially where high levels of performance are the objective. As such, SBM has contributed greatly to our understanding of nutrient requirements for ruminants, be this dairy cows, beef animals or sheep and goats. The large data base on SBM composition, rumen-degradation, microbial protein production or digestibility and intermediary metabolism of AA make it an exceptionally well known and suited ingredient for reliable ration formulations and (estimating) essential nutrient supply. These considerations allow for a better prediction of performance on SBM -based diets relative to many other ingredients.

Summary and conclusions

This paper has briefly summarized the major nutritional developments during the last 100 years of SBM as an animal feed ingredient. Also, emphasis was placed on discussing the anti-nutritional factors in SBM and why their removal or inactivation are fundamental to improving animal performance, especially in poultry and swine. Using as a reference and a starting point the paper by Hayward (1970), we have highlighted the last 50 years. SBM is today the number one supplier of digestible amino acids for poultry and swine world-wide. Also, an important supplier of metabolizable and net energy. As Hymowitz (1990) wrote in reference to the success of soybeans as a crop in the U.S. highlighting that it was not an instant success, but rather the result of a long process, a summation of efforts and hard work, the same can be said about the success story of SBM as an animal feed ingredient.

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