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NUTRITIONAL EVALUATION BY GROWING PIGS OF FIVE SOURCES OF FULL-FAT SOYBEANS GROWN IN DIFFERENT GEOGRAPHICAL REGIONS IN THE UNITED STATES

BY

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THESIS

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ABSTRACT

Three experiments were conducted to determine the nutritional composition and digestibility of five sources of extruded full-fat soybeans (FFSB) from different geographical locations in the United States when fed to growing pigs. In experiment 1, the objective was to determine the standardized ileal digestibility (SID) of AA in five sources of FFSB. Six ileal cannulated growing barrows (initial body weight: 85.50 ± 3.34 kg) were randomly allotted to a six by six Latin square design with six periods and six experimental diets. Six diets included each one FFSB source as the sole source of AA, and a N-free diet was used to determine basal endogenous losses of CP and AA. Full-fat soybean contained CP, acid hydrolyzed ether extract, and insoluble dietary fiber with an average of 338.0, 171.9, and 176.4 g per kg, respectively. The SID of CP and most indispensable AA were no differences among the five sources of FFSB, except that the SID of Glu in FFSB source 02 was greater ($P = 0.05$) than in FFSB source 01. In experiment 2, the objective was to test the hypothesis that there is no difference in the digestible energy (DE), the metabolizable energy (ME) among five sources of FFSB. Four-eight pigs (initial BW = 30.86 ± 1.64 kg) were randomly allotted to complete block design with six experimental diets and eight replicate pigs per diet. Each diet consisted of 40% of FFSB and corn, then a basal diet based on corn as the only energy source contributor of energy to the diet were formulated. The concentration of ME in corn was 15.73 MJ per kg dry matter (DM), and ME in the five sources of FFSB was 20.74, 19.85, 20.59, 20.19, and 21.22 MJ per kg DM, respectively. The ME in FFSB source 05 was greater ($P < 0.05$) than the ME in FFSB sources 02 and 04. There were no differences in DE:GE, ME:DE, or ME:GE among the five sources of FFSB or between FFSB and corn. In experiment 3, the objective was to determine the standardized total tract digestibility (STTD) of P in five sources of FFSB. Eighty growing barrows (initial body weight: 16.73 ± 3.16

kg) were allotted to a randomized complete block design with ten diets and eight replicate pigs per diet. Five diets contained each source of FFSB as the only source of P and five additional diets were formulated by adding 1000 phytase units (FTU)/kg of microbial phytase to the original five diets. Among the diets that did not include microbial phytase, FFSB source 05 was greater ($P < 0.05$) than the STTD of P in the other sources of FFSB. Among the diets containing microbial phytase, no differences among the five sources of FFSB were observed (interaction, $P < 0.05$). Microbial phytase improved ($P < 0.05$) the STTD of P in all sources of FFSB. In conclusion, only minor differences in chemical composition among five sources of FFSB grown in different regions of the United States were observed and the SID of CP and the majority of indispensable AA were not different among the five sources. Full-fat soybeans contained more ME than corn, but there were only minor differences among sources in ME. Likewise, the STTD of P in FFSB was not different among sources if microbial phytase was used, and microbial phytase improves the STTD of P in FFSB. The results indicate that the growing region does not significantly impact the digestibility of amino acids in FFSB or the concentration of ME. Additionally, the use of phytase appears to mitigate the influence of growing location on the STTD of P in FFSB.

Keywords: Amino acids, Energy, Full-fat soybeans, Phosphorus

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CHAPTER 1: INTRODUCTION

Soybeans were introduced in the United States from China during the last part of the 18th century (Shurtleff and Aoyagi, 2004). The first varieties were used to produce soy sauce, but soybeans were also used as forage crops (Ruiz et al., 2020). After World War II, soybean production increased due to increased demand for soybean oil (Guo et al., 2022). However, because only around 20 % of the soybean is oil, production of the protein-rich meal from the crushing of soybeans also increased (Shurtleff and Aoyagi, 2004). Incorporation of soybeans into crop rotation systems also yielded benefits for other crops because of the nitrogen-fixing activities of soybeans in the soil (Hymowitz, 2008). Therefore, soybeans became a novel and significant crop. However, it was discovered in the 1950'ties that a diet based on corn and soybean meal and fortified with minerals and vitamins, can supply all nutrient needs of pigs and poultry, which resulted in increased soybean production (Basuchaudhuri, 2020). In 2021, soybeans in the U.S. were planted on 87.2 million acres, which yielded a post-harvest value of $57.5 billion (USDA, 2023) and soybeans occupied 33% of the total crop area in the U.S. (ASA, 2022). Brazil, the United States, and Argentina are the major global producers of soybeans.

Soybean represents approximately 90 % of U.S. oilseed production (USDA, 2023). Soybean oil is used as an edible vegetable oil globally, with a portion being used for various industrial applications. Recently, federal subsidies have resulted in increased demand for soybean oil for biodiesel production, which has led to an increase in soybean crushing in the U.S. (USDA, 2024). However, because crushing yields both oil and meal, the production of soybean meal has also increased (Krishnan and Jez, 2018). The high nutritional value of soybean meal is primarily attributed to the amino acid composition of soy protein. Although the majority of the soybeans grown in the U.S. are crushed to yield oil and soybean meal, feeding of full-fat soybean

(FFSB) may also provide the amino acids pigs need, but there is a lack of knowledge about the nutritional value of FFSB when fed to pigs. However, due to the presence of trypsin inhibitors in raw soybeans, their full nutritional potential is realized only after undergoing a certain degree of heat treatment (Liener, 1981). In the conventional crushing of soybeans, heat treatment is achieved during the toasting step that is needed to remove residual solvent used in fat extraction. However, if FFSB are used without oil removal, an alternative procedure for heat treatment is needed (Grant, 1989; Goebel and Stein, 2011) and several processing techniques can be used (Deak et al., 2008). These methods may have varying effects on the nutritional composition of FFSB, but due to the relatively low cost, extrusion of FFSB to achieve the needed inactivation of trypsin inhibitors is often used. However, differences in extrusion parameters may introduce variations in nutrient availability and digestibility, thereby influencing the overall nutritional value of the end products (Alonzo et al., 2000). Considering this complexity, the objective of the research outlined in this thesis is to determine the nutritional value of FFSB sourced from different regions within the U.S. Specifically, this work aims to determine the digestibility of amino acids, determine values of digestible and metabolizable energy, and determine the digestibility of phosphorus in FFSB when fed to growing pigs. By determining nutritional value of FFSB from different geographical origins, results of this work may be used in diet formulations for pigs.

LITERATURE CITED

Alonso, R., A. Aguirre, and F. Marzo. 2000. Effects of extrusion and traditional processing methods on antinutrients and in vitro digestibility of protein and starch in faba and kidney beans. Food Chem. 68:159-165. doi:0.1016/S0308-8146(99)00169-7.

ASA. American Soybean Association. 2022. Soy stats: A reference guide to important soybean facts and figures. Soybean Assoc. USA: https://soygrowers.com/wp-content/uploads/2022/06/22ASA-002-Soy-Stats-Final-WEB.pdf. Accessed April 2024.

Basuchaudhuri, P. 2020. Introduction In: Physiology of soybean plant (1st ed.). CRC Press. Boca Raton, FL, USA. Pages 9-10. doi:10.1201/9781003089124

Deak, N. A., L. A. Johnson, E. W. Lusas, and K. C. Rhee. 2008. Soy protein products, processing, and utilization. In L. A. Johnsan, P. J. White, R. Galloway (Eds.), Soybeans: Chemistry, Production, Processing, and Utilization. AOCS Press. Urbana, Illinois, USA. Pages 661–724. doi:10.1016/B978-1-893997-64-6.50022-6.

Goebel, K. P., and H. H. Stein. 2011. Ileal digestibility of amino acids in conventional and low-Kunitz soybean products fed to weanling pigs. Asian-Australian J. Anim. Sci. 24, 88–95. doi:10.5713/ajas.2011.90583

Grant, G. 1989. Anti-nutritional effects of soybean: A review. Prog. Food Nutr. Sci. 13: 317-348.

Guo, B., L. Sun, S. Jiang, H. Ren, R. Sun, Z. Wei, H. Hong, X. Luan, J. Wang, X. Wang, D. Xu, W. Li, C. Guo, and L. Qiu. 2022. Correction to: Soybean genetic resources contributing to sustainable protein production. Theor. Appl. Genet. 135: 4123. doi:10.1007/s00122-022-04241-6

Hymowitz, T. 2008. The history of the soybean. In Johnson, L., White, P. J., and Galloway, R. (eds) Soybeans: Chemistry, Production, Processing and Utilization. Urbana, IL, USA: AOCS Press. Pages 1–32. doi:10.1016/B978-1-893997-64-6.50004-4

Krishnan, H. B., and J. M. Jez. 2018. The promise and limits for enhancing sulfur-containing amino acid content of soybean seed. Plant Sci. 272:14–21. doi:10.1016/j.plantsci.2018.03.030

Liener, I. E. 1981. Factors affecting the nutritional quality of soya products. J. Am. Oil Chem. Soc. 58: 406–415. doi:10.1007/BF02582390

Ruiz, N., C. M. Parsons, H. H. Stein, C. N. Coon, J. E. van Eys, and R. D. Miles. 2020. A review: 100 years of soybean meal. Feedstuff online edition, Jan. 2020. Accessed April, 2024. https://nutrition.ansci.illinois.edu/node/1566.

Shurtleff, W., and A. Aoyagi. 2004. History of world soybean production and trade – part 1 and 2. Accessed April 2024. https://www.soyinfocenter.com/HSS/production_and_trade1.php.

USDA. 2023. United States Department of Agriculture. National Agricultural Statistics Service. https://www.ers.usda.gov/topics/crops/soybeans-and-oil-crops/related-data-statistics/. Accessed April 2024.

USDA. 2024. United States Department of Agriculture. U.S. renewable diesel production growth drastically impacts global feedstock trade. https://fas.usda.gov/data/us-renewable-diesel-production-growth-drastically-impacts-global-feedstock-trade. Accessed August 2024.

CHAPTER 2: Use of full-fat soybeans in diets for pigs: A literature review

INTRODUCTION

Soybeans are used as the protein source in most diets for pigs due to their favorable amino acid (AA) profile and concentration, with around 26 percent of the United States production used in diets for swine (Stein et al., 2008). Full-fat soybeans (FFSB) contain antinutritional factors (ANF) that adversely affect nutrient digestibility and growth performance in pigs, particularly during early stages of development (Stein et al., 2008). Therefore, FFSB need thermal processing to eliminate antinutritional factors before being used in diets for pigs. Heat treatment following solvent extraction can successfully inactivate the majority of undesirable components in raw soybeans, but residual fiber and oligosaccharides that are present in soybeans after crushing are inadequately utilized as energy sources (Baker, 1999). Well-processed FFSB is a valuable feed ingredient due to its high protein quality and energy content (Thanabalan et al., 2021).

Extrusion is expected to result in both chemical and physical changes in feed ingredients and thereby increasing the digestibility of nutrients and energy by pigs (Kiarie et al., 2020; Milani et al., 2022), which is important because energy represents one of the costliest components in pig diets (Noblet, 2007). Extrusion also has the potential to deactivate heat-sensitive ANF such as trypsin inhibitors and antigenic proteins, thereby potentially improving digestibility of crude protein in soybeans and enhancing growth performance (Kim et al., 1999; Milani et al., 2022). Extrusion involves softening and increase in flexibility of moistened, starchy, and proteinaceous food materials through a die using a combination of moisture, pressure, heat, and mechanical shear (Riaz, 2020). During extrusion, the material, typically preconditioned to a moisture content of 15 to 30 percent, is fed into the extruder through a screw

feeder, entering the feeding zone where a screw with increased depth and pitch transports and homogenizes the raw material. The material then progresses into the compression zone where the screw reduces in depth and pitch, leading to higher shear rate, temperature (110 to 180ºC) and pressures to be between 20 and 30 atm (Zhang et al., 2018; Maurya and Said, 2014). These parameters are crucial for maintaining the nutritional characteristics of the end products at optimal levels for ingredients fed to pigs.

PROCESSING OF FULL-FAT SOYBEANS

Full-fat soybeans contain approximately 37 percent crude protein, 19 percent crude fat, and 4 percent crude fiber (Marty et al., 1994; NRC 2012). Processing of FFSB typically involves dehulling, grinding, and heat processing using extrusion, expansion, jet-sploding, flaking, cooking, roasting, and micronizing, or microwaving (Lehmali and Jafari, 2019). Processing without using heat may include salt treatment, fermentation, germination, pressure cooking, soaking and urea treatment (Lehmali and Jafari, 2019). Proper processing improves the digestibility of AA, fats, and other nutrients in diets for pigs (Kim et al., 2000).

Dry extrusion processing is used on some farms and in some feed mills that may not have access to expelling or solvent extraction facilities. The extruder operated in a continuous manner and the friction that is generated due to the pressure results in an elevated temperature for a relatively short time (Wiriyaumpaiwong et al., 2004). Because of this elevated temperature, trypsin inhibitors and some other ANF will be inactivated.

ANTI-NUTRITIONAL FACTORS IN SOYBEANS

Soybeans and co-products of soybeans provide protein and AA in diets for pigs, but soybeans also contain secondary plant metabolites, which are used to protect the beans from predators. These components are known as ANF and include trypsin inhibitors, antigenic proteins, and phytic acids. The trypsin inhibitors are the most studied ANF in soybeans because they reduce protein absorption in animals, resulting in depressed digestibility of AA and reduced growth performance (Jezierny et al., 2010; Milani et al., 2022).

Trypsin inhibitors in soybeans include Kunitz inhibitors and Bowman-Birk inhibitors that inhibit the activity of trypsin, chymotrypsin, and other proteases. Trypsin is produced in the pancreas in an inactive form known as trypsinogen, which becomes activated when entering the small intestine during digestion. Ingesting trypsin inhibitors results in formation of an irreversible complex between trypsin and the inhibitors, which results in a reduction of trypsin enzyme levels in the intestine and disrupts the protein digestion process (Vagadia et al., 2017), which reduces absorption of nutrients. The Kunitz trypsin inhibitor is a small stable monomeric non-glycosylated globulin-type protein in soybean seeds. The protein comprises 181 AA residues, has a molecular weight of 21.5 kDa, and an isoelectric point of pH 4.5 (Kunitz, 1947). The Kunitz inhibitors function as storage proteins, safeguarding the plant against microbial proteases and regulating endogenous proteases within the plant; however, the atypical AA composition imparts inhibitory properties when consumed (Vagadia et al., 2017). The Bowman-Birk inhibitor consists of 71 AA and contains a total of 7 disulfide bonds. It is present in smaller quantities compared with the Kunitz inhibitor and, therefore, has not been as extensively studied as the Kunitz inhibitor (Birk, 1985). Trypsin inhibitors in raw whole soybeans range from 16 to

27 mg per g (Vagadia et al., 2017), but their concentration is reduced up to 90 percent after the treatment, resulting in less than 3 mg per g in correctly processed soybeans.

Phytic acid is a saturated cyclic acid that is used to conserve P naturally in plants, also known as phytate or phytin. Six phosphates are bound to an inositol ring and 36 to 53 percent of the total P in soybeans is bound to phytate (Silva et al., 2021; Zhai et al., 2022). Therefore, the digestibility of P in FFSB is low when fed to pigs, because pigs do not have the enzyme needed to release P from phytate. The digestibility of P by pigs depends on three factors: phytate-P content; non-phytate-P content; and phytase activity of the diet (Eeckhout and De Paepe, 1994). Phytic acid can also bind to bi- and trivalent cations in the acidic environment of the stomach or at the neutral pH of the small intestine. This interaction inhibits the absorption of Ca, P, and some trace elements, and possibly also reduces digestibility of energy and other nutrients by pigs (Schlemmer et al., 2001; Zhai et al., 2022). Phytate-bound phosphorus is only partially degraded in swine due to the limited secretion of phytase along the gastrointestinal tract. However, exogenous phytase may be added to diets containing soybean meal to increase P-digestibility (Rojas and Stein, 2012; Sotak-Peper et al, 2016). The concentration of phytate in the diet, however, may influence the effectiveness of supplemental phytase (Kemme et al., 2006; Zhai et al., 2022).

Antigenic proteins when ingested cross the intestinal barrier and sensitize the immune system so that subsequent consumption may elicit a hypersensitive response (Radcliffe et al. 2019). In soybeans, the most immunologically active multi-subunit globulins are beta conglycinin and soy glycinin, which account for 70–80% of the total antigenic proteins (Wang et al., 2023b). Beta conglycinin is considered the primary antigen responsible for soybean hypersensitivity in weaned pigs (Zheng et al., 2014). This hypersensitivity response results in

immunological abnormality and is a predominantly Th2-type immune response, mediated by IgE and associated with the increase of mast cell numbers and histamine release. This may affect digestion and absorption of nutrients resulting in deprived performance and incidence of diarrhea in weaned pigs (Sun et al., 2008).

METHODS FOR DETERMINATION OF DIGESTIBILITY AND CONCENTRATION OF NUTRIENTS IN INGREDIENTS FED TO PIGS

In feed formulation, accurate estimation of concentration and digestibility of energy and nutrients in ingredients is crucial for their optimal use. This approach helps reduce feed costs and environmental impact, eventually leading to greater efficiency. Methods to estimate digestibility of energy and nutrients in feed ingredients have been optimized in recent decades, and in vivo digestibility experiments are the most common methods to estimate digestibility (Kong and Adeola, 2014; Zhang and Adeola, 2017). Dietary energy, AA, vitamins, and minerals are all crucial when formulating diets for swine, but research has predominantly concentrated on determining digestibility of energy and AA. This focus is largely due to the fact that energy and AA represent the major costs in swine nutrition (Kong and Adeola, 2014).

The standard procedure for calculating digestibility involves assessing the difference between the amount of feedstuff consumed and the nutrient or energy content excreted in the feces. This is typically done using a total collection method. Accurate measurement of both fecal output and feed intake is essential, as these values are generally expressed as percentages. Feces are collected over a period of several days, commonly ranging from 4 to 5 days, depending on the experimental design (Adeola, 2001). In certain experimental setups, it is also necessary to accurately measure urine output. Before the collection period, pigs are acclimated to the experimental conditions and diet through a pre-trial adaptation phase. This phase, conducted in a

metabolism crate, allows the animals to adjust to the new diet and environment, thereby ensuring that subsequent measurements reflect the true digestibility of the diet under stable conditions.

In some instances, conducting a total collection of feces may be impractical or unfeasible. When this is the case, digestibility can be estimated using an index method. This method involves the use of an index compound, which should be completely indigestible, non-toxic, exhibit a stable passage rate through the gastrointestinal tract, and be amenable to standard analytical techniques (Zhang and Adeola, 2017). Common index compounds include chromium oxide (Cr_2O_3) and titanium dioxide (TiO_2), which are typically incorporated into the diet at concentrations of 0.1% to 0.5% (Adeola, 2001). To ensure accurate results, the index method requires a minimum adaptation period of five days. This period allows the pig metabolism to stabilize and adjust to the index compound, thereby reducing potential discrepancies in the digestibility measurements (Clawson et al., 1955).

In vivo digestibility studies employ either direct or difference methods (Adeola, 2001). The direct method requires that the test ingredient can be used as the sole provider of the nutrient for which digestibility is measured. However, some test ingredients cannot be used as the sole source of the nutrient due to low palatability, anti-nutritional factors, or nutritional imbalance (Kong and Adeola, 2014). In that case, a basal diet, which does not contain the test ingredient is formulated and a second diet that contains the test ingredient and the basal diet is also formulated. The digestibility of nutrients in the test ingredient can then be calculated by the difference between the basal diet and test diet (Adeola, 2001).

Digestible and metabolizable energy

Pigs do not fully utilize all the energy in their diets, but a direct measurement of the energy allocated to various physiological functions in pigs is nearly impossible. In the assessment of energy requirements for swine, the energy partitioning system is divided into three primary categories: heat production, tissue formation, and waste products (NRC, 2012). The total gross energy of the diet serves as the input gross energy. Digestible energy (DE) is calculated by subtracting the gross energy of feces from the input of gross energy. Subsequently, metabolizable energy (ME) is determined by further subtracting the gross energy of urine, with the assumption that gaseous losses are negligible in pigs (NRC, 2012). Because ME represents the energy that is available for metabolism, values for ME are generally preferred for accurately formulating diets to meet the energy requirements of pigs. The DE and ME can be determined either by the direct method or by the indirect method. Adjustments to ME can be made to account for the effects of retained nitrogen from protein, as pigs are unable to fully retain nitrogen from dietary protein. However, such corrections for nitrogen equilibrium may not be applicable to growing pigs, as they retain substantial amounts of nitrogen that are not typically utilized as an energy source (NCR, 1998).

Ileal digestibility of amino acids

Digestibility assays have been extensively used for estimating the availability of AA in feed ingredients. The most preferred method includes ileal digesta collection using a T-cannula that is surgically inserted 10 to 20 cm anterior to the ileo-colic valve, because this is the least invasive method and does not involve the surgical resection of parts of the lower digestive tract (Stein et al., 2007). Usually, the test diet is supplemented for 7 days, where the initial 5 days are considered the adaptation period to the test diets and ileal digesta are collected on days 6 and 7

for 9 h per day (Stein et al., 1998). The collection process involves affixing a plastic bag to the cannula barrel with a cable tie. Digesta flowing into the bag are collected, and the bags are replaced either when full or at intervals not exceeding 30 minutes. Following collection, samples are stored at −20 ºC to inhibit bacterial degradation of AA. To determine standardized ileal digestibility, apparent ileal digestibility values are adjusted for basal endogenous losses of AA. Basal endogenous losses are typically assessed using nitrogen-free diets (Kong and Adeola, 2014). Stein et al. (2007) previously defined that the ileal digestibility of AA can be represented as apparent ileal digestibility, standardized ileal digestibility, or true ileal digestibility, depending on how ileal endogenous AA losses are factored into the calculation of AA digestibility. However, for practical diet formulation use of values for standardized ileal digestibility are preferred because these values are additive in mixed diets (Stein et al., 2005).

Phosphorus digestibility

The absorption of P mainly occurs in the small intestine, where it is also secreted endogenously (NRC, 2012). The process by which biological systems maintain stability while adjusting to changing conditions is crucial for regulating P levels in the body. However, the large intestine does not significantly influence this regulatory process, as it neither absorbs P nor secretes endogenous P in measurable amounts. Therefore, the apparent AID of P is consistent with the total tract digestibility values (Bohlke et al., 2005; NRC, 2012). Given that total tract digestibility assessments are generally simpler and more cost-effective to perform than determination of ileal digestibility, P digestibility values are primarily derived from total tract digestibility measurements. Apparent total tract digestibility (ATTD) can be determined via total collection methods using direct or index approaches (Zhang and Adeola, 2017). When calculating P digestibility, it is important to adjust ATTD for basal endogenous phosphorus loss (EPL) to

obtain values for the standardized total tract digestibility (STTD) of P. Data from a large number of experiments have determined that EPL is remarkable constant and average around 190 mg of P per kilogram of dry matter intake (NCR, 2012). Thus, if the ATTD of P for a specific feed ingredient has been established, the STTD can be calculated ensuring additivity of values from different ingredients in a mixed diet (NRC, 2012).

FULL-FAT SOYBEANS IN ANIMAL NUTRITION

Full-fat soybean is an excellent source of energy and protein, with special value in diets for young pigs where a high energy concentration is beneficial (Ravindran et al., 2014). The level of inclusion of FFSB in diets depends on its cost relative to other sources of energy and protein. Approximately 95 percent of all soybeans harvested in the United States (equivalent to 2.94 million of metric tons) is used for animal feed, seed, and others purposes different from human consumption (United Soybean Board, 2024). Specific data for FFSB usage in the United States are not available. However, the price of commercially available fats, including soy oil, has increased in recent years due to the increased biodiesel production (Statista, 2024), and inclusion of fats in animal diets has become price prohibitive. Therefore, there is interest in identifying high-energy ingredients that may be used in diets for livestock, which has increased the interest in using FFSB in animal diets.

Swine

Incorporation of FFSB in swine diets provides a straightforward method for increasing the concentration of fat and energy in diets without requiring specialized spraying equipment or complex liquid handling and storage processes. Typically, lipid feed components need to be

heated to a liquid state prior incorporation into feed; however, this step is unnecessary with FFSB. The lipids in FFSB also have greater resistance to oxidation and rancidity, allowing for longer storage compared with individually stored fats and oils (Toomer et al., 2024). In young pigs, FFSB may be included by up to 50% of conventional soybean meal without affecting growth performance parameters (Kim and Kim, 1997). Palacios et al. (2004) demonstrated that ANF in FFSB can be responsible for reduced animal weight gain and daily feed intake, however adequate heat treatment of FFSB resulting in greater or equal growth performance parameters compared with using SBM. Also, FFSB can be used instead of SBM in diets for growing-finishing pigs without negative effects on slaughtering performance and meat quality, if inclusion is lower than 30% (Zollitsch et al., 1993). Inclusion of 12.2% FFSB improved the concentration of lactose, protein, and solid-not-fat in milk of sows, which resulted in increased weight at weaning of pigs (Zhou et al., 2016).

Values for DE and ME have been estimated to be 4,193 and 3,949 Kcal per kg in FFSB fed to pig, which is greater than in yellow dent corn and SBM (NRC, 2012). Most energy obtained from FFSB is derived from protein and fat, which is highly digestible (Kim et al., 2013). The ATTD of GE in FFSB is between 88 and 90% which is less than or equal to cereal grains (Cervantes-Pahm et al., 2013; Wang et al., 2023a). The hindgut disappearance of GE, however, is greater in FFSB than in SBM, due to the high content of fat that improves lower gastric passage and energy concentration (Mateos et al., 1982; Kim et al., 2013; Paternostre et al., 2021). In FFSB, the SID of CP was determined to be 79 ± 10.12 % in pigs (Stein, 2021). Compared with other cereal grains, FFSB protein has relatively high SID of Lys and Trp, that are limiting AA in other grains, such as corn (Stein et al., 2008). The SID of Lys, Met, Thr, and Trp was 81%, 80%, 76%, and 83%, respectively (NRC, 2012; Stein, 2021). The standardized total

tract digestibility (STTD) of P is around 48% (NRC, 2012; Stein, 2021). Based on results of previous research, the digestibility of P may be greater than in corn, but equal to SBM (NRC, 2012). The ATTD of P in FFSB was reported to be 67.5% if exogenous microbial phytase was included in the diet (Kiarie et al., 2020).

Other species

Incorporation of FFSB produced from organic soybeans represents an option for raising organic poultry for animal niche markets globally (Dal Bosco et al., 2012). Indeed, inclusion of up to 22.5 % FFSB in diets for poultry has no effects on small intestinal mucosa, nutrient retention, or growth performance, but inclusion of more than 22.5 %, reduced weight gains due to reduced absorptive mucosal surface area in the upper small intestine, which resulted in decreased feed intake (Mirghelenj et al., 2013).

Full-fat soybeans, along with other soybean derived products, may be used as alternatives to fish meal in aquafeed for various fish species, including Atlantic salmon, rainbow trout, sea bream, sea bass, and Atlantic halibut (Zhou et al., 2017). However, results of research have been inconsistent, ranging from positive to negative effects on growth and other performance metrics, and this variability is likely a result of ANF in soybeans (Karalazos et al., 2007). Consequently, the impact of incorporating FFSB into fish diets is influenced by processing and treatment of the soybeans, the inclusion level, the specific fish species, and the age or size of the fish (Neves et al., 2024).

Soybean meal may be processed to minimize the ruminal degradation of its high-quality protein while preserving its intestinal absorption, but extrusion of FFSB effectively protects dietary protein and fat from ruminal fermentation, thereby increasing the availability of protein

and energy for absorption in the small intestine (Bailoni et al., 2004). This process not only supports equal or improved milk yield and composition, but also helps reduce the need for imported bypass protein sources, such as fish meal (Bailoni et al., 2004). In addition, FFSB used in calf starters have resulted in improvements in growth performance and feed efficiency (ZeidAli-Nejad et al., 2018).

CONCLUSIONS

The nutritional characteristics of FFSB indicate that FFSB contains a greater profile of AA than cereal grains, such as corn. Therefore, FFSB can be used in combination with other grains to complement the deficiency of amino acids in other grains, but it is limited by its ANF content. Full-fat soybeans contain approximately 37 percent crude protein, 19 percent crude fat, and 4 percent crude fiber. As a feed ingredient, FFSB provides energy to the pig mostly by the content of fat and protein. However, limited research has been conducted to evaluate the efficacy of feeding FFSB to pigs, but existing data indicate that processing techniques, particularly extrusion, may enhance the nutritional value of FFSB by reducing ANF levels and improving nutrient digestibility.

LITERATURE CITED

Adeola, O. 2001. Digestion and balance techniques in pigs. Pages 895-908 in Swine Nutrition. A. J. Lewis and L. L. Southern. ed. CRC Press, Boca Raton, FL.

Bailoni L, A. Bortolozzo, R. Mantovani, A. Simonetto, S. Schiavon, and G. Bittante. 2004. Feeding dairy cows with full fat extruded or toasted soybean seeds as replacement of soybean meal and effects on milk yield, fatty acid profile and CLA content. Ital. J. Anim. Sci. 3:243–258. doi:10.4081/ijas.2004.243

Baker, D. H. 1999. Nutritional constraints to use of soy products by animals. In: Soy in Animal Nutrition; J. K. Drackley, Ed.; Federation of Animal Science Societies: Savoy, IL, USA 2000. Pages 1–12.

Birk, Y. 1985. The Bowman-Birk inhibitor. Trypsin- and chymotrypsin-inhibitor from soybeans. Int. J. Pept. Protein Res. 25:113-131. doi:10.1111/j.1399-3011.1985.tb02155.x

Bohlke, R. A., R. C. Thaler, and H. H. Stein. 2005. Calcium, phosphorus, and amino acid digestibility in low-phytate corn, normal corn, and soybean meal by growing pigs. J. Anim. Sci. 83:2396–2403. doi:10.2527/2005.83102396x

Cervantes-Pahm, S. K., Y. Liu, and H. H. Stein. 2013. Comparative digestibility of energy and nutrients and fermentability of dietary fiber in eight cereal grains fed to pigs. J. Sci. Food Agric. 94:841-849. doi:10.1002/jsfa.6316

Clawson, A. J., J. T. Reid, B. E. Sheffy, and J. P. Willman. 1955. Use of chromium oxide in digestion studies with swine. J. Anim. Sci. 14:700-709. doi:10.1093/ansci/14.3.700

Dal Bosco, A., C. Mugnai, S. Ruggeri, S. Mattioli, and C. Castellini. 2012. Fatty acid composition of meat and estimated indices of lipid metabolism in different poultry genotypes reared under organic system. Poult. Sci. 91:2039-2045. doi:10.3382/ps.2012-02228

Eeckhout, W., and M. De Paepe. 1994. Total phosphorus, phytate-phosphorus and phytase activity in plant feedstuffs. Anim. Feed Sci. Technol. 47:19-29. doi:10.1016/0377-8401(94)90156-2

Jezierny, D., R. Mosenthin, and E. Bauer. 2010. The use of grain legumes as a protein source in pig nutrition: a review. Anim. Feed Sci. Technol. 157:111–128. doi:10.1016/j.anifeedsci.2010.03.001.

Karalazos, V., J. Treasurer, C. J. Cutts, R. Alderson, T. F. Galloway, S. Albrektsen, J. Arnason, N. MacDonald, I. Pike, and J. G. Bell. 2007. Effects of fish meal replacement with full-fat soy meal on growth and tissue fatty acid composition in Atlantic cod (Gadus morhua). J. Agric. Food Chem. 55:5788–5795 doi:10.1021/jf0629383

Kemme, P. A., U. Schlemmer, Z. Mroz, and A. W. Jongbloed. 2006. Monitoring the stepwise phytate degradation in the upper gastrointestinal tract of pigs. J. Sci. Food Agric. 86:612–622. doi:10.1002/jsfa.2380

Kiarie, G. E., I. A. Parenteau, C. Zhu, N. E. Ward, and A. J. Cowieson. 2020. Digestibility of amino acids, energy, and minerals in roasted full-fat soybean and expelled-extruded soybean meal fed to growing pigs without or with multienzyme supplement containing fiber-degrading enzymes, protease, and phytase. J. Anim. Sci. 98:skaa174. doi:10.1093/jas/skaa174

Kim, B. G., D. Y. Kil, and H.H. Stein. 2013. In growing pigs, the true ileal and total tract digestibility of acid hydrolyzed ether extract in extracted corn oil is greater than in intact sources of corn or soybean oil. J. Anim. Sci. 91:755-763. doi:10.2527/jas.2011-4777

Kim, I. H., J. D. Hancock, D. B. Jones, and P. G. Reddy. 1999. Extrusion processing of low-inhibitor soybeans improves growth performance of early-weaned pigs. Asian-Australas. J. Anim. Sci. 12:1251–1257. doi:10.5713/ajas.1999.1251

Kim I. H., J. D. Hancock, and R. H. Hines. 2000. Influence of processing method on ileal digestibility of nutrients from soybeans in growing and finishing pigs. Asian-Australas. J. Anim. Sci. 13:192-199. doi:10.5713/ajas.2000.192

Kim, I. H., and C. S. Kim. 1997. The effects of dry-extruded whole soybean on growth performance and immune response in early-weaned pigs. Korean J. Anim. Sci 39:681–692.

Kong, C., and O. Adeola. 2014. Evaluation of amino acid and energy utilization in feedstuff for swine and poultry diets. Asian Australas J. Anim Sci. 27:917-925. doi:10.5713/ajas.2014.r.02

Kunitz, M. 1947. Crystalline soybean trypsin inhibitor II. General properties. Gen. Physiol. Biophys. 30:291-310. doi: 10.1085/jgp.30.4.291

Lehmali, I., and M. Jafari. 2019. Effect of different thermal and non-thermal processing methods on chemical composition, quality indicators and apparent nutrient digestibility of full-fat soybean. Braz. J. Poultry Sci. 21:1–8. doi:10.1590/1806-9061-2019-1099

Marty, B. J., E. Chávez, and C. F. M. De Lange. 1994. Recovery of amino acids at the distal ileum for determining apparent and true ileal amino acid digestibilities in growing pigs fed various heat-processed full-fat soybean products. J. Anim. Sci. 72:2029–2037. doi:org/10.2527/1994.7282029x

Mateos, G.G., J.L. Sell, and , J.A. Eastwood. 1982. Rate of food passage (transit time) as influenced by level of supplemental fat. Poult. Sci. 61, 94-100. doi:10.3382/ps.0610094

Maurya, A. K., and P. P. Said. 2014. Extrusion processing on physical and chemical properties of protein rich products-an overview. J. Bioresour. Eng. Technol. 2:61–67.

Milani, N. C., V. R. C. De Paula, C. P. F. Azevedo, A. A. Sedano, L. B. Scarpim, H. M. Junior, D. H. A. Duarte, A. C. Carciofí, M. A. Neto, and U. S. Ruiz. 2022. Effects of extrusion on ileal and total tract nutrient and energy digestibility of untoasted soybean meal in weanling pigs. Anim. Feed Sci. Technol. 284:115206. doi:10.1016/j.anifeedsci.2022.115206

Mirghelenj, S. A., A. Golian, H. Kermanshahi, and A. R. Raji. 2013. Nutritional value of wet extruded full-fat soybean and its effects on broiler chicken performance. J. Appl. Poult. Res. 22:410-422. doi:10.3382/japr.2012-00602

Neves, N. O. D. S., J. De Dea Lindner, L. Stockhausen, F. R. Delziovo, M. Bender, L. Serzedello, L. A. Cipriani, N. Ha, E. Skoronski, E. Gisbert, I. Sanahuja, and T. E. P. Fabregat. 2024. Fermentation of plant-based feeds with lactobacillus acidophilus improves the survival and intestinal health of juvenile Nile tilapia (Oreochromis niloticus) reared in a biofloc system. Animals. 14:332. doi:10.3390/ani14020332

Noblet, J. 2007. Net energy evaluation of feeds and determination of net energy requirements for pigs. Rev. Bras. Zootec. 36:277–284. doi:org/10.1590/S1516-35982007001000025

NRC. 1998. Nutrient Requirements of Swine. 10th ed. National Academy Press, Washington, DC, USA.

NRC. 2012. Nutrient requirements of swine: 11th revised edition. The National Academies Press, Washington, DC, USA.

Palacios, M, R. Easter, K. Soltwedel, C. Parsons, M. Douglas, T. Hymowitz, T. Pettigrew. 2004. Effect of soybean variety and processing on growth performance of young chicks and pigs. J. Anim. Sci. 82:1108–1114. doi:10.2527/2004.8241108x

Paternostre, L., J. De Boever, and S. Millet. 2021. Interaction between fat and fiber level on nutrient digestibility of pig feed. Anim. Feed Sci. Technol. 282, 115126. doi:10.1016/j.anifeedsci.2021.115126

Schlemmer, R. K., D. Jany, A. Berk, E. Schulz, and G. Rechkemmer. 2001. Degradation of phytate in the gut of pigs-pathway of gastrointestinal inositol phosphate hydrolysis and enzymes involved. Arch. Anim. Nutr. 55:255-280. doi:10.1080/17450390109386197

Silva, V. M., F. F. Putti, P. J. White, and A. Rodrigues dos Reis. 2021. Phytic acid accumulation in plants: Biosynthesis pathway regulation and role in human diet. Plant Physiol. Biochem. 164:132-146. doi:10.1016/j.plaphy.2021.04.035

Sotak-Peper, K. M., J. C. González-Vega, and H. H. Stein. 2016. Effects of production area and microbial phytase on the apparent and standardized total tract digestibility of phosphorus

in soybean meal fed to growing pigs. J. Anim. Sci. 94:2397-2402. doi:10.2527/jas.2016-0353

Statista. 2016. Average prices for soybean oil worldwide from 2014 to 2025 (in nominal U.S. dollars per mt). https://www.statista.com/statistics/675815/average-prices-soybean-oil-worldwide/. Accessed Sept. 2024.

Stein, H. H. 2021. Monogastric Nutrition Laboratory. Feed ingredient database. University of Illinois at Urbana-Champaign. Accessed September 20, 2024. https://nutrition.ansci.illinois.edu/static/feed_database.html

Stein, H. H., C. Pedersen, A. R. Wirt, and R. A. Bohlke. 2005. Additivity of values for apparent and standardized ileal digestibility of amino acids in mixed diets fed to growing pigs. J Anim Sci. 83:2387–95. doi:10.2527/2005.83102387x

Stein, H. H., L. L. Berger, J. K. Drackley, G. C. Fahey Jr, D. C. Hernot, and C. M. Parsons. 2008. Nutritional properties and feeding values of soybeans and their coproducts. Soybeans. AOCS Press, Urbana, IL, USA. Pages 613–660. doi:10.1016/B978-1-893997-64-6.50021-4.

Stein, H. H., C. F. Shipley, and R. A. Easter. 1998. Technical note: A technique for inserting a T-cannula into the distal ileum of pregnant sows. J. Anim. Sci. 76:1433-1436. doi:10.2527/1998.7651433x

Sun, P., D. Li, Z. Li, B. Dong, and F. Wang. 2008. Effects of glycinin on IgE-mediated increase of mast cell numbers and histamine release in the small intestine. J. Nutr. Biochem. 19:627-633. doi:10.1016/j.jnutbio.2007.08.007

Toomer, O. T., E. O. Oviedo-Rondón, M. Ali, M. Joseph, T. Vu, B. Fallen, and R. Mian. 2024. Full-fat soybean meals as an alternative poultry feed ingredient—feed processing methods and utilization—review and perspective. Animals. 14:2366. doi:10.3390/ani14162366

Ravindran, V., M. Abdollahi, and M. Bootwalla. 2014. Nutrient analysis, apparent metabolisable energy and ilea amino acid digestibility of full fat soybean for broilers. J. Anim. Sci. 197, 233-240. doi:10.1016/j.anifeedsci.2014.08.014

Radcliffe, J. S., L. F. Brito, L. Reddivari, M. Schmidt, E. M. Herman, and A. P. Schinckel. 2019. A swine model of soy protein-induced food allergenicity: implications in human and swine nutrition. Anim. Front. 9:2–59. doi: 10.1093/af/vfz025

Riaz M. N. 2020. Extrusion processing of oilseed meals for food and feed production. In: Bailey's industrial oil and fat products. F. Shahidi, Ed.; John Wiley & Sons, Ltd., Texas, USA. Pages 1-34. doi:10.1002/047167849X.bio061.pub2

Rojas, O. J., and H. H. Stein. 2012. Digestibility of phosphorus by weanling pigs of fermented and conventional soybean meal without and with microbial phytase. J. Anim. Sci. 90:1506–1512. doi:10.2527/jas.2011-4103

Thanabalan, A., M. Mohammadigheisar, and E. G. Kiarie. 2021. Amino acids and energy digestibility in extruded or roasted full fat soybean fed to broiler chickens without or with multienzyme supplement containing protease, phytase, and fiber degrading enzymes. Poult. Sci. 100:12. doi:10.1016/j.psj.2021.101511

United Soybean Board. 2024. US soybean meal feed use by species; whole soybean consumption by country.

https://marketviewdb.unitedsoybean.org/dashboards/?bi=US_Meal_FeedUsebySpecies_Annual. Accessed August 2024.

Vagadia, B. H., S. K. Vanga, and V. Raghavan. 2017. Inactivation methods of soybean trypsin inhibitor - a review. Trends Food Sci. Technol. 64:115–125. doi:10.1016/j.tifs.2017.02.003

Wang, L., Z. Zeng, Q. Hu, L. Wang, H. Shi, C. Lai, and S. Zhang. 2023a. Determination and prediction of the available energy and amino acids digestibility of full-fat soybean fed to growing pigs. J Anim Sci. 101, skac395. doi:10.1093/jas/skac395

Wang, L., Y. Liu, D. Zhang, H. Ding, S. Feng, C. Zhao, J. Wu, and X. Wang. 2023b. Soybean antigen protein-induced intestinal barrier damage by trigging endoplasmic reticulum stress and disordering gut microbiota in weaned piglets. Molecules. 28:6500. doi:10.3390/molecules28186500

Wiriyaumpaiwong, S., S. Soponronnarit, and S. Prachayawarakorn. 2004. Comparative study of heating processes for full-fat soybeans. J. Food Eng. 65:371–382. doi:org/10.1016/j.jfoodeng.2004.01.036

ZeidAli-Nejad A., G. R. Ghorbani, S. Kargar, A. Sadeghi-Sefidmazgi, A. Pezeshki, and M. H. Ghaffari. 2018. Nutrient intake, rumen fermentation and growth performance of dairy calves fed extruded full-fat soybean as a replacement for soybean meal. Animal. 12:733–740. doi:10.1017/S1751731117002154

Zhai, H., O. Adeola, and J. Liu. 2022. Phosphorus nutrition of growing pigs. Anim. Nutr. 9:127-137. doi:10.1016/j.aninu.2022.01.010

Zhang, F., and O. Adeola. 2017. Techniques for evaluating digestibility of energy, amino acids, phosphorus, and calcium in feed ingredients for pigs. Anim. Nutr. 3:344-352. doi:10.1016/j.aninu.2017.06.008

Zhang, J. C., L. Liu, H. Z. Liu, A. Yoon, S. S. H. Rizvi, and Q. Wang. 2018. Changes in conformation and quality of vegetable protein during texturization process by extrusion. Crit. Rev. Food Sci. 59:3267–3280. doi:10.1080/10408398.2018.1487383

Zheng, S., G. Qin, H. Tian, and Z. Sun. 2014. Role of soybean β-conglycinin subunits as potential dietary allergens in piglets. Vet. J. 199:434-438. doi:10.1016/j.tvjl.2013.11.020

Zhou, Z., E. Ringø, E. Olsen, and S. K. Song. 2017. Dietary effects of soybean products on gut microbiota and immunity of aquatic animals: A review. Aquac. Nutr. 24:644–665. doi:10.1111/anu.12532

Zhou, P., G. Luo, L. Che, Y. Lin, S. Xu, Z. Fang, and D. Wu. 2016. Extruded full-fat soybean as a substitute for soybean meal and oil in diets for lactating sows: the effect on litter performance and milk composition. Anim. Prod. Sci. 57:1725–1730. doi:10.1071/AN15179.

Zollitsch, W., W. Wetscherek, and F. Lettner. 1993. Use of differently processed full-fat soya beans in a diet for pig fattening. Anim. Feed Sci. Technol. 41:237-246. doi:10.1016/0377-8401(93)90016-D

CHAPTER 3: CHEMICAL COMPOSITION AND STANDARDIZED ILEAL DIGESTIBILITY OF AMINO ACIDS IN FIVE SOURCES OF FULL-FAT SOYBEANS FED TO GROWING PIGS

ABSTRACT

An experiment was conducted to determine the chemical composition of full-fat soybeans (FFSB) from different regions of the United States (source 01, 02, 03, 04, and 05) and to test the hypothesis that there is no difference in the standardized ileal digestibility (SID) by growing pigs of crude protein (CP) and amino acids (AA) among FFSB sources regardless of where in the United States they were grown. The ground soybeans were extruded and analyzed for dry matter, gross energy, nitrogen, AA, acid-hydrolyzed ether extract, ash, minerals, starch, insoluble dietary fiber, soluble dietary fiber, sugars, and trypsin inhibitors (TI). In the SID experiment, each source of FFSB was included in one diet as the only source of AA and a N-free diet was formulated to determine basal endogenous losses of AA; thus, a total of six diets were prepared. Six growing barrows (initial body weight: 85.50 ± 3.34 kg) that had a T-cannula installed in the distal ileum were allotted to a 6 × 6 Latin square design with six diets and six 7-day periods. Ileal digesta were collected from the cannulas on day 6 and 7 of each period and SID of CP and AA was calculated. Results indicated that the main nutrients in FFSB were CP, acid hydrolyzed ether extract, and insoluble dietary fiber with an average of 338.0, 171.9, and 176.4 g per kg, respectively. The FFSB also contained an average of 10.3 g per kg starch, 112.5 g per kg sugars, 54.4 g per kg minerals, and 21.3 MJ per kg gross energy. The unanalyzed rest fraction in FFSB was 20.6 kg per kg on average. Results from the SID experiment demonstrated that there were no differences among the five sources of FFSB for the SID of CP and AA, except that the SID of

Glu in FFSB source 02 was greater (P = 0.05) than in FFSB source 01. There was also a tendency (P < 0.10) for the SID of Arg, Gly, and Tyr to be greater in FFSB source 02 compared with FFSB source 01 and the SID of Tyr in FFSB source 02 also tended (P < 0.10) to be greater than in FFSB sources 04 and 05. In conclusion, only minor differences in chemical composition among five sources of FFSB grown in different regions of the United States were observed and the SID of CP and the majority of indispensable AA were not different among the five sources indicating that growing region does not affect digestibility of AA in FFSB.

Key words: amino acids, chemical composition, digestibility, full-fat soybean, pig

Abbreviations: AA, amino acids; AID, apparent ileal digestibility; CP, crude protein; DM, dry matter; FFSB, full-fat soybean; SID, standardized ileal digestibility; SBM, soybean meal; SEM, standard error of means; TI, trypsin inhibitors.

INTRODUCTION

Soybean protein is used in diets for pigs and poultry to balance the low concentration of amino acids (AA) in cereal grains (Basuchaudhuri, 2020), and the high nutritional value of the soybean is determined largely by the AA composition of the protein (Liener, 1981). Full-fat soybeans (FFSB) contain approximately 370 g per kg of crude protein (CP) and 180 to 200 g per kg of oil (Marty et al., 1994; NRC 2012). Soybean oil contains linoleic acid, vitamin E, and lecithin (Ravindran et al., 2014), which are valuable nutrients in swine diets. However, raw soybeans also contain several antinutritional factors including protease inhibitors, which depress growth rate and decrease efficiency of feed utilization (Grant, 1989), because the protein digesting enzymes are impaired by the trypsin inhibitors (TI), which reduce AA digestibility (Waldroup, 1982; Goebel and Stein, 2011). Therefore, all soybean products need to be heat

treated to inactivate the protease inhibitors before they can be fed to pigs. In the traditional crushing of soybeans, oil is extracted using a solvent and this process is followed by toasting to remove residual solvent. However, the toasting process also inactivates TI, and the resulting ingredient is called solvent extracted soybean meal (SBM). It is also possible to use FFSB directly in diets for pigs and poultry without extraction of oil, but to inactivate the TI, it is necessary to heat treat the soybeans before usage (Goebel and Stein, 2011; Ravindran et al., 2014), which can be accomplished by extrusion. However, to successfully incorporate FFSB in diets for pigs, the nutritional value needs to be determined. The chemical composition of soybeans has been reported (Grieshop et al., 2003; Baker et al., 2010; Kiarie et al., 2020), and it was demonstrated that the nutritional composition is influenced by genotype, geographical growing region, and environmental conditions (Qin et al., 1998). There is, however, a lack of data for the composition of FFSB collected from different growing areas in the United States, and it is not known if the nutritional value of FFSB is constant among different growing regions within the United States. There is also limited information about the digestibility of AA in FFSB when fed to pigs, and the impact of growing region of FFSB on the digestibility of AA has not been reported. Therefore, the objective of this work was to test the hypothesis that growing region of soybeans does not influence chemical composition or the standardized ileal digestibility (SID) of CP and AA when fed to growing pigs.

MATERIALS AND METHODS

The protocol for the SID experiment was submitted to and approved by the Institutional Animal Care and Use Committee at the University of Illinois prior to initiation of the animal

work (Protocol number: 21247). Pigs that were the offspring of Line 800 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN) were used.

Soybeans were collected from different regions of the United States representing the entire growing area from Pennsylvania to North Dakota. Samples were collected and arbitrarily labelled source 01, 02, 03, 04, and 05, respectively. The raw soybeans were coarsely ground using a 9.5 mm screen in a MixMill™ (A.T. Ferrell Company Inc., Hereford, TX, USA). The grinder was flushed and cleaned between each source of FFSB to prevent cross contamination. The ground soybeans were then processed with high-shear dry extruders using 2 paired extruders (Model 2000, Insta-Pro® International, Grimes, IA, USA) that each had a capacity of 1,000 kg per hour. The 2 extruders used identical process parameters and were adjusted to maintain a minimum processing temperature of 160 °C. The extruded FFSB were cooled with ambient air using a rotary drum cooler (Model 900, Insta-Pro® International, Grimes, IA, USA) to produce the final product of FFSB (Tables 3.1, 3.2, 3.3, and 3.4).

Analysis of soybeans

Samples of the extruded FFSB were finely ground through a 0.5 mm screen, using a grain mill (500G Swing Type Grain Mill, RRH, Zhejiang, China) before analysis. Dry matter (DM) was measured using a drying oven for 2 h at 135 °C (method 930.15; AOAC Int., 2019) and ash was analyzed by oven drying at 600°C for 2 h (method 942.05; AOAC Int., 2019). Gross energy was analyzed using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA) and the internal standard was benzoic acid. Crude protein was calculated as N × 6.25 and N was measured using the combustion procedure (Method 990.03; AOAC Int., 2019) on a LECO FP628 (LECO Corp., Saint Joseph, MI, USA). Amino acids were analyzed on a Hitachi Amino

Acid Analyzer, Model No. L8800. (Hitachi High Technologies America, Inc; Pleasanton, CA) using ninhydrin for postcolumn derivatization and norleucine as the internal standard. Prior to analysis, samples were hydrolyzed with 6N HCl for 24 h at 110°C [method 982.30 E(a); AOAC Int., 2019]. Methionine and Cys were determined as Met sulfone and cysteic acid after cold performic acid oxidation overnight before hydrolysis [method 982.30 E(b); AOAC Int., 2019]. Tryptophan was determined after NaOH hydrolysis for 22 h at 110°C [method 982.30 E(c); AOAC Int., 2019]. Trypsin inhibitor concentrations were analyzed (method Ba 12-75; AOCS, 2006) and phytic acid was analyzed as well (Ellis et al., 1977). Acid-hydrolyzed ether extract was analyzed using 3 N HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY, USA) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY, USA; method 2003.06; AOAC Int., 2019). Ingredients were analyzed for insoluble dietary fiber and soluble dietary fiber according to method 991.43 (AOAC Int., 2019) using the AnkomTDF Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber was calculated as the sum of insoluble and soluble dietary fiber. Sugars including glucose, fructose, maltose, sucrose, stachyose, raffinose, and verbascose were analyzed using high-performance liquid chromatography (Dionex App Notes 21 and 92). Macro minerals and micro minerals were analyzed (i.e., Ca, P, Mg, K, Na, S, Cu, Fe, Mn, Zn) by an inductively coupled plasma spectroscopy method (method 985.01 A, B, and C; AOAC, 2019) after wet ash sample preparation (method 975.03 B(b); AOAC Int., 2019). Total starch was analyzed in the five sources of FFSB by the amyloglucosidase-alpha-amylase procedure corresponding to the enzymatically hydrolyzed starch converted to glucose, and subsequent analysis of glucose by spectroscopy (method 996.11; AOAC Int., 2019).

Digestibility of CP and AA

Each source of FFSB was included in one diet as the only source of AA and a N-free diet was formulated to determine basal endogenous losses of AA; thus, a total of six diets were prepared (Tables 3.5 and 3.6). Vitamins and minerals were included in all diets to meet current nutrient requirements, for growing pigs (NRC, 2012). Diets were provided at a level of 3.2 times the maintenance energy requirement for growing pigs (i.e., 197 kcal metabolizable energy per kg body weight$^{0.60}$; NRC, 2012). The daily allotment of feed was provided each day at 0800 h and water was available at all times. All diets contained 4 g per kg chromic oxide as an indigestible marker.

Six growing barrows (initial body weight: 85.50 ± 3.34 kg) that had a T-cannula installed in the distal ileum were allotted to a 6 × 6 Latin square design with 6 diets and six periods (Kim and Stein, 2009). Therefore, there were 6 replicate pigs per diet. Cannulas were installed in the pigs when they had a body weight of approximately 25 kg and pigs had been used in a previous experiment before being fed a commercial grower diet for two weeks and then allotted to the current experiment. Pigs were individually housed in pens (1.2 × 1.5 m) in an environmentally controlled room and each pen was equipped with a feeder, a drinking nipple, and fully slatted-floors. Pig weights were recorded at the beginning of each period and at the conclusion of the experiment.

Each experimental period lasted 7 days where the initial 5 days were considered the adaptation period to the diets and ileal digesta were collected on days 6 and 7 for 9 h per day using standard procedures (Stein et al., 1998). Cannulas were opened at the beginning of collection and a 225-mL plastic bag was attached to the cannula barrel using a cable tie. Digesta flowing into the bag were collected and bags were replaced whenever they were full or at least

once every 30 min. All samples were stored at −20 ºC after collection to prevent bacterial degradation of AA (Lee et al., 2021). On the completion of one experimental period, animals were deprived of feed overnight and the following morning, a new experimental diet was offered.

At the conclusion of the experiment, ileal digesta samples were thawed and mixed within animal and diet, and a sub-sample was lyophilized and finely ground prior to chemical analysis. Diets and ileal digesta samples were analyzed for DM, CP, and AA using the methods explained for the FFSB sources. Chromium was analyzed in experimental diets and ileal digesta using the Inductive Coupled Plasma Atomic Emission Spectrometric method (method 990.08; AOAC Int., 2019). Samples were prepared for analysis using nitric acid-perchloric acid (method 968.08D(b); AOAC Int., 2019).

Calculations

For each analysis of each source of FFSB, all analyzed components were added and subtracted from the concentration of dry matter in each ingredient to calculate the rest fraction using the following equation (Fanelli et al., 2023):

Rest fraction= [dry matter - (crude protein + acid hydrolyzed ether extract + ash + total dietary fiber + sucrose + stachyose + raffinose + verbascose + starch)]

Phytate-P was calculated by multiplying the analyzed phytate by 0.282 (Tran and Sauvant, 2004), and nonphytate-P was calculated as the difference between total P and phytate-P. the average of each analysis for the 5 sources of FFSB was calculated and the standard deviation was calculated for each average value. The concentration of AA expressed as a percent of CP was calculated using the analyzed concentration of each AA divided by the analyzed concentration of CP in each source of FFSB and multiplied by one hundred and expressed as g

per kg of protein. The standard deviation and average of all samples from each FFSB source within each group of analysis were calculated.

In the SID experiment, basal endogenous losses of CP and AA were calculated from pigs fed the N-free diet (Stein et al., 2007). Apparent ileal digestibility (AID) of CP and all AA was calculated using the analyzed CP, AA, and Cr concentrations in the diets and ileal digesta samples. The SID values were calculated by correcting AID values for the basal endogenous losses of CP and AA (Stein et al., 2007). Concentrations of standardized ileal digestible AA in each source of FFSB were calculated by multiplying the concentration of each AA by the calculated SID of that AA.

The homogeneity of the variances and normality of data were confirmed by the UNIVARIATE procedure and data were analyzed using the PROC MIXED procedure (SAS Inst. Inc., 2018). Outliers were identified as values that deviated from the predicted mean by more than two times the internally studentized residual within the treatment (Tukey, 1977). The model included diet as the fixed effect and period and animal as random effects. Mean values were calculated using the LSMeans statement and if the model was significant, means were separated using the PDIFF statement with Tukey's adjustment. Pig was the experimental unit, and results were considered significant at $P \leq 0.05$ and $0.05 < P < 0.10$ was considered a tendency.

RESULTS

Chemical composition of FFSB

The main nutrients in FFSB were CP, acid hydrolyzed ether extract, and insoluble dietary fiber, which on average were present in concentration of 338.0 ± 4.83, 171.9 ± 3.74, and 176.4 ± 8.07 g per kg, respectively, and the average gross energy was 21.3 ± 0.24 MJ per kg. The 5 sources of FFSB also contained an average of 44.7 ± 3.83 g per kg of sucrose, and 37.5 ± 5.77 g

per kg of stachyose. As shown in Table 3.2, Among the indispensables AA, Leu (86.1 ± 0.9 g per kg), Arg (78.9 ± 0.92 g per kg), and Lys (73.5 ± 0.86 g per kg) were present in the greatest concentrations. Phytic acid averaged 11.20 ± 0.89 g/kg, which corresponded to 3.12 ± 0.22 g per kg phytate bound P (Table 3.4). Because total P averaged 3.90 ± 0.29 g per kg, non-phytate P was calculated to be 0.76 ± 0.16 g per kg. Calcium analyzed 2.08 ± 0.38 g per kg and K had an average of 12.04 ± 0.54 g per kg. Among microminerals Fe was present at the greatest concentration (1169.74 ± 383.61 mg per kg), followed by Zn (404.54 ± 46.62 mg per kg), and Mn (306.66 ± 50.21 mg per kg). The rest fraction in FFSB was between -8.3 and 41.3 g per kg, with an average of 20.6 ± 17.3 g per kg.

Digestibility of AA

Pigs remained healthy during the experiment, no feed refusals were observed, and all pigs completed the experiment. During statistical analysis, 1 pig fed the diet containing FFSB source 01 was detected as an outlier and data from this pig was not included in the statistical analysis. All other data were included in the analysis. The AID of CP and most AA was not different among the five sources of FFSB (Table 3.7). However, the AID of Arg, Cys, and Glu was greater ($P \leq 0.05$) in FFSB source 02 than in FFSB source 01. The AID of Tyr was also greater ($P \leq 0.05$) in FFSB source 02 compared with FFSB sources 04 and 05 and the AID of Gly tended ($P = 0.054$) to be greater in source 02 than in source 01.

No differences in the SID of CP and AA were observed among the five sources of FFSB except that the SID of Glu in FFSB source 02 was greater ($P = 0.05$) than in FFSB source 01 (Table 3.8). However, there was a tendency ($P < 0.10$) for the SID of Arg, and Gly to be greater in FFSB source 02 compared with FFSB source 01, and the SID of Tyr in FFSB source 02 also tended ($P < 0.10$) to be greater than in sources 04 and 05.

The concentration of all standardized ileal digestible AA in FFSB source 02 was greater ($P < 0.05$) than in FFSB source 03, except for the concentration of Thr, Trp, and Ser (Table 3.9). The concentration of digestible Arg, His, Met, Thr, Cys, Glu, Gly and Ser in FFSB source 02 was also greater ($P < 0.05$) than in FFSB source 01. However, FFSB source 01 had a greater concentration of digestible Arg, Trp, and Tyr than FFSB source 03. Likewise, FFSB sources 04 and 05 had greater ($P < 0.05$) concentration of standardized ileal digestible Arg, His, Lys, Met, and Cys than FFSB source 03, but FFSB sources 04 and 05 had concentrations of standardized ileal digestible Ile, Phe, and Glu that were less ($P < 0.05$) than in FFSB source 02, whereas FFSB source 04 had a lower ($P < 0.05$) concentration of digestible Trp than FFSB from other origins. In contrast, the greatest concentration of digestible Trp among all sources, except source 01, was in source 05 ($P < 0.05$). The concentration of digestible His was less ($P < 0.05$) in source 04 than in source 02, and the concentration of digestible Leu in source 05 was less ($P < 0.05$) than in source 02. Full-fat soybeans sources 04 and 05 had greater ($P < 0.05$) concentration of digestible Met and Cys than source 01, and FFSB source 04 also had a greater ($P < 0.05$) concentration of digestible Arg and Ser than FFSB source 01.

DISCUSSION

Soybeans are one of the primary agricultural commodities globally with an annual production averaging around 389 million metric tons (USDA, 2023) and Brazil, the United States, and Argentina are the major global producers of soybeans. In 2021, soybeans occupied 33% of the total crop area in the U.S. (ASA, 2022). The predominant use of soybeans involves crushing to yield soy oil and soybean meal (Galkanda-Arachchige et al., 2021), but if oil is not removed, FFSB can be a source of energy and nutrients in animal diets, provided that they are

heat treated to inactivate TI (Goebel and Stein, 2011). Extrusion of FFSB involves exposing soybeans to an appropriate pressure and temperature, which causes inactivation of TI, denaturation of proteins, enhanced protein digestibility, and reduced concentration of TI and phytic acid (Alonso et al., 2000; Milani et al., 2022).

The sources of FFSB used in this work were from different locations in the United States, but the processing was similar for all sources and completed at the same facility (Insta-Pro® International, Grimes, IA, USA). The concentrations of dry matter in each source of FFSB used in this work was greater than previously reported (Cervantes-Pahm and Stein, 2008; Baker et al., 2010; NRC, 2012), which likely is a consequence of the extrusion that provides heat to the beans, and therefore, reduces moisture concentration. The concentration of CP was in agreement with data reported by Cervantes-Pahm and Stein (2008), but less than reported by other authors (Baker et al., 2010; NRC, 2012). Concentrations of gross energy, total dietary fiber, and ash were greater, and fat was less than reported by other authors (NRC, 2012; Yoon and Stein, 2013; Ravindra et al., 2014), and concentration of sucrose, stachyose and raffinose, were in agreement with previous values (Baker et al., 2011; NRC, 2012; Yoon and Stein, 2013). Trypsin inhibitors in the FFSB used in this work were reduced to between 5.7 and 7.7 TIU per mg in DM basis, which is slightly greater than reported by others (Baker et al., 2010; Kiarie et al., 2020; Wang et al., 2023). The concentrations of TI in FFSB are negatively correlated with energy utilization in pigs, as demonstrated in previous studies (Wang et al., 2023). This relationship suggests that higher levels of TI may impair the digestive efficiency and overall energy availability from FFSB in swine diet. Also, high value of TI results in decreased SID of AA (Goebel and Stein, 2011; Yáñez et al., 2019). In contrast high temperatures during extrusion may cause Maillard reaction (González-Vega et al., 2011; Kim et al., 2012; Oliveira et al., 2020), which will also

reduce the SID of AA, specifically Lys. However, the fact that Lys in the sources of FFSB used in the experiment was greater than 60 g per kg protein indicates that samples were not heat damaged (González-Vega et al., 2011).

The concentration of phytic acid, phytate-P, and the percentage of phytate-P of total P in FFSB was greater than reported values (NRC, 2012; Cheng and Hardy, 2003). Phytate in FFSB can reduce not only the digestibility of P, but also of Ca and micronutrients. Therefore, a large part of phytate-P is not used by pigs, but is excreted in the feces, but extrusion may reduce the levels of phytic acid in feed ingredients (Alonso et al., 2000). The concentration of Ca in FFSB analyzed in this work was less than previous values (Kiarie et al., 2020). The mineral composition of soil has a significant impact on the nutrient mineral concentration in crops, including FFSB, which may be the reason for the lower concentration of Ca (Ohlrogge, 1960). Nevertheless, the concentration of most other minerals analyzed in the FFSB samples from the experimental was consistent with previously reported values (Cheng and Hardy, 2003; NRC, 2012; Kiarie et al., 2016).

The rest fraction was calculated at 20.6 ± 17.23 g per kg for the 5 sources of FFSB. It is not clear what the composition of the rest fraction is, but it is possible that some of the analyzed components may have been underestimated due to the high concentration of fat in the samples as has been show for dietary fiber (Mertens, 2003), and other proximate components (Shurson et al., 2021). However, having a rest fraction of 10 to 50 g per kg is not uncommon when practical feed ingredients are analyzed (Navarro et al., 2018; Fanelli et al., 2023). The AA contents measured in this study were consistent among the 5 sources of FFSB. These results align with findings reported by NRC (2012) and Kaewtapee et al. (2017), particularly when comparable temperature conditions were applied during the study. The AA compositions in FFSB used in

this work were comparable to those found in SBM (NRC, 2012). However, the total amount of AA in FFSB was 20 to 35% lower, primarily due to the oil extraction process used in soybean meal production, which results in approximately 18% acid hydrolyzed ether extract in FFSB. Nevertheless, the levels of indispensable AA in FFSB remained higher than those found in cereal ingredients, such as corn (NRC, 2012). Indispensable AA cannot be synthesized by pigs, making sufficient intake through feed essential for optimal growth performance (Rezaei et al., 2013), this highlights FFSB not only as a high-quality protein ingredient but also as a valuable source of energy, particularly beneficial for pigs during the weaning and growing stages.

The observation that only minor differences in the SID of CP and AA among the 5 sources of FFSB were calculated indicates that growing region within the United States does not impact protein quality. This observation is in agreement with data indicating that the SID of AA in SBM is not impacted by growing region (Sotak-Peper et al., 2016; Lagos and Stein, 2017). The values for SID of CP and AA in the FFSB used in this experiment were close to previous values (Cervantes-Pahm and Stein, 2008; Baker et al., 2010; Kiarie et al., 2020). Previous data demonstrated that the SID of AA in FFSB was lower than in SBM (NRC, 2012; Yáñez et al., 2019), but that may be due to either over-heating or under-heating of the FFSB. Also, the concentration of TI serves as a common indicator of soybean quality, particularly in relation to the SID of Lys. This is due to the strong negative correlation observed between TI levels and lysine digestibility (Kaewtapee et al., 2024). However, values for SID of AA in this experiment were close to the values reported by Goebel and Stein (2011) and Yáñez et al. (2019) for SBM. It is also possible that if the FFSB are not dehulled, the fiber in the diets may reduce the SID of AA because fiber often results in reduced digestibility of AA (Baker et al., 2010; Fouhse et al., 2016; Sanchez-Zannatta et al., 2023). In contrast, the fat in FFSB may increase SID of AA due to a

slower gastric and intestinal emptying, which increases the time to digest proteins by proteolytic enzymes (Cervantes-Pahm and Stein, 2008; Goebel and Stein, 2011). The observation that the calculated concentration of standardized ileal digestible AA did differ somewhat among some of the sources of FFSB may be related to the number of sunlight hours that soybeans receive during the growing season, because shading stress impacts soybean senescence, resulting in increased retention of nitrogen in soybean leaves, stems, and seeds (Deng et al., 2024). Because non-amino acid nitrogen is not utilized by pigs, this nitrogen does not have a nutritional value. Nevertheless, the observation that the differences in concentration of digestible AA among sources were minor, although in some instances significant, indicates that the AA value of FFSB is relatively constant regardless of the growing region in the United States.

CONCLUSION

The chemical composition of five sources of full-fat soybean was consistent regardless of where they were grown. Although there were minor differences in concentrations of crude protein and some amino acids among the full-fat soybeans, these differences were relatively small. Specifically, a reduction in crude protein and some amino acids was observed in full-fat soybean source 03 compared with the other sources. However, only minor variations in the standardized ileal digestibility of amino acids were noted, indicating that the origin of the full-fat soybeans did not impact amino acid digestibility. Likewise, concentrations of digestible amino acids were mostly consistent among the five sources of full-fat soybean, regardless of their geographical origin. Thus, it is concluded that the chemical composition and standardized ileal digestibility of crude protein and amino acids in full-fat soybeans produced in the United States are not significantly influenced by the location where the soybeans were grown.

TABLES

Table 3.1. Analyzed nutrient composition of five sources of full-fat soybeans FFSB[1]

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	Average	SD
Dry matter, g/kg	937.1	934.7	920.4	941.8	936.1	934.0	7.20
Gross energy, MJ/kg	21.6	21.1	21.2	21.0	21.6	21.3	0.24
Crude protein, g/kg	338.4	341.6	329.9	336.4	343.9	338.0	4.83
Total dietary fiber, g/kg	171.8	209.9	198.9	197.2	187.1	193.0	12.82
Soluble dietary fiber, g/kg	4.7	25.4	12.4	29.0	13.2	16.9	8.96
Insoluble dietary fiber, g/kg	168.1	185.5	186.4	168.2	173.9	176.4	8.07
Acid-hydrolyzed ether extract, g/kg	177.5	170.8	168.8	167.5	174.9	171.9	3.74
Ash, g/kg	54.6	55.5	53.7	54.6	53.5	54.4	0.73
Starch, g/kg	8.0	6.3	16.4	15.0	5.7	10.3	4.53
Trypsin inhibitors, units per mg	5.9	6.2	6.6	7.7	5.7	6.4	0.72
Sucrose, g/kg	42.4	47.4	40.4	42.4	50.9	44.7	3.83
Raffinose, g/kg	6.9	7.1	7.1	5.8	5.5	6.5	0.67
Stachyose, g/kg	36.5	45.3	30.5	32.6	43.1	37.6	5.77
Verbascose, g/kg	2.4	4.4	2.9	2.3	3.3	3.1	0.76
Rest fraction[3], g/kg	41.3	-8.3	31.5	26.2	12.1	20.6	17.23

[1]All data except dry matter were calculated on the basis of 880 g per kg dry matter.

[2]Glucose, fructose, and maltose in the five sources of FFSB were analyzed but not detectable.

[3]Rest fraction = calculated using equation: [DM − (crude protein + acid-hydrolyzed ether extract + ash + total dietary fiber + sugars + starch)] (Fanelli et al., 2023).

Table 3.2. Amino acid (AA) composition of amino acids of five sources of full-fat soybean (FFSB)[1]

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	Average	SD
Indispensable AA							
Arg	25.0	25.2	24.0	25.4	25.4	25.0	0.52
His	9.4	9.6	9.0	9.4	9.5	9.4	0.21
Ile	18.0	18.3	17.3	17.8	17.8	17.8	0.32
Leu	27.5	27.7	26.3	27.4	27.4	27.2	0.49
Lys	23.2	23.4	22.3	23.5	23.9	23.3	0.54
Met	4.7	4.9	4.6	5.0	5.1	4.9	0.19
Phe	18.5	18.5	17.6	18.0	18.3	18.2	0.35
Thr	13.2	13.9	13.4	13.8	13.9	13.7	0.29
Trp	4.7	4.5	4.3	3.2	4.9	4.3	0.60
Val	18.5	18.5	17.3	18.2	18.5	18.2	0.47
Dispensable AA							
Ala	15.3	15.5	14.7	15.3	15.5	15.3	0.29
Asp	39.5	40.0	38.4	40.4	40.3	39.7	0.72
Cys	4.9	5.4	5.1	5.9	5.7	5.4	0.38
Glu	61.8	65.2	59.7	63.4	62.5	62.5	1.84
Gly	15.1	15.6	14.6	15.4	15.4	15.2	0.35
Pro	17.3	18.4	16.6	17.8	17.7	17.5	0.57
Ser	13.8	14.5	14.3	14.7	14.5	14.4	0.30
Tyr	12.1	11.9	11.4	12.2	12.2	12.0	0.32

[1]All data were calculated on the basis of 880 g per kg dry matter.

Table 3.3. Concentration of amino acids (AA) in full-fat soybeans (FFSB) expressed as g per kg of crude protein

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	Average	SD
Indispensable AA							
Arg	78.8	78.8	77.7	80.6	78.7	78.9	0.92
His	29.7	30.0	29.0	30.0	29.5	29.6	0.38
Ile	56.9	57.1	55.9	56.4	55.2	56.3	0.66
Leu	86.8	86.5	84.9	86.9	85.0	86.1	0.90
Lys	73.3	73.3	72.2	74.7	74.1	73.5	0.86
Met	14.7	15.2	14.8	16.1	15.9	15.3	0.57
Phe	58.3	57.9	56.8	57.2	56.9	57.4	0.58
Thr	41.6	43.6	43.2	43.9	43.2	43.1	0.78
Trp	14.7	14.1	13.9	10.0	15.0	13.5	1.82
Val	58.3	57.9	55.9	57.8	57.4	57.5	0.81
Dispensable AA							
Ala	45.2	45.5	44.6	45.6	45.1	45.2	0.35
Asp	116.8	117.2	116.5	120.0	117.3	117.6	1.25
Cys	14.4	15.7	15.4	17.5	16.7	15.9	1.07
Glu	182.6	191.0	180.9	188.6	181.8	185.0	4.04
Gly	44.7	45.8	44.4	45.8	44.8	45.1	0.59
Pro	51.1	53.8	50.4	52.8	51.4	51.9	1.23
Ser	40.8	42.5	43.5	43.6	42.1	42.5	1.03
Tyr	35.8	34.7	34.5	36.4	35.5	35.4	0.70

Table 3.4. Analyzed mineral composition of five sources of full-fat soybeans (FFSB)[1]

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	Average	SD
Phytic acid	10.30	11.50	10.30	12.70	11.20	11.20	0.89
Total phosphorus	3.70	4.20	3.70	4.30	3.60	3.90	0.29
Phytate-P[2]	2.90	3.20	2.90	3.50	3.10	3.12	0.22
Phytate-P, g/kg of total P	644.50	636.80	658.80	684.10	712.50	667.34	27.74
Nonphytate-P[3]	0.80	1.00	0.80	0.70	0.50	0.76	0.16
Total Ca	1.90	2.00	2.80	2.00	1.70	2.08	0.38
Mg	1.70	1.80	1.90	2.00	1.70	1.82	0.12
K	12.10	12.70	11.90	12.40	11.10	12.04	0.54
Na	2.60	2.60	2.60	2.60	2.60	2.60	0
S	2.60	2.90	2.60	3.40	2.90	2.88	0.29
Microminerals, mg/kg							
Cu	193.6	193.6	193.6	193.6	193.6	193.6	0
Fe	743.70	803.60	1119.00	1767.80	1414.60	1169.74	383.61

Table 3.4 (cont.)

Mn	239.60	348.00	294.50	378.20	273.00	306.66	50.21
Zn	347.10	430.80	403.90	476.90	364.00	404.54	46.62

[1]All data were calculated on the basis of 880 g per kg dry matter.

[2]Phytate-P was calculated by multiplying the analyzed phytate by 0.282 (Tran and Sauvant, 2004).

[3]Nonphytate-P was calculated as the difference between total P and phytate-P.

Table 3.5. Ingredient composition of experimental diets, as-fed basis[1]

Ingredient, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	N-free
FFSB	400	400	400	400	400	-
Cornstarch	473	473	473	473	473	682.5
Sucrose	100	100	100	100	100	200
Soybean oil	-	-	-	-	-	40
Solka floc[2]	-	-	-	-	-	40
Dicalcium phosphate	9	9	9	9	9	15.5
Ground limestone	5	5	5	5	5	4
Magnesium oxide	-	-	-	-	-	1
Potassium carbonate	-	-	-	-	-	4
Sodium chloride	4	4	4	4	4	4
Vitamin-mineral premix[3]	5	5	5	5	5	5
Chromic oxide	4	4	4	4	4	4

[1]FFSB = full-fat soybeans.

[2] Fiber Sales and Development Corp., Urbana, OH, USA.

[3]The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D_3 as cholecalciferol, 1,660 IU; vitamin E as $_{DL}$-alpha-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamine mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B_{12}, 0.03 mg; $_{D}$-

Table 3.5 (cont.)

pantothenic acid as D-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydriodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

Table 3.6. Nutrient composition of experimental diets containing five sources of full-fat soybeans (FFSB), as-fed basis

Ingredient, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	N-free
Dry matter	911.6	917.7	900.7	908.5	908.5	901.1
Crude protein	138.6	140.1	135.9	136.5	140.5	2.2
Indispensable amino acids						
Arg	10.6	11.7	9.7	9.2	9.7	0.1
His	4	4.5	3.7	3.6	3.8	0
Ile	7.4	8.3	7.2	6.9	7.2	0.3
Leu	11.9	13	11.2	10.7	11.1	0.3
Lys	10	11.1	9.3	9.1	9.5	0.1
Met	2	2.3	1.8	1.8	1.9	0
Phe	7.8	8.6	7.4	7	7.3	0.1
Thr	6	6.6	5.3	5.2	5.4	0
Trp	1.8	2.1	1.7	2.1	1.9	0.1
Val	7.5	8.5	7.4	7.1	7.4	0.1
Dispensable amino acids						
Ala	6.7	7.4	6.3	6.1	6.3	0.2
Asp	17.5	19.4	16.2	15.8	16.4	0.1
Cys	2.1	2.6	2.1	2.3	2.2	0
Glu	27.6	31	26	25.7	26.4	0.3

Table 3.6 (cont.)

Gly	6.6	7.3	6.2	6.1	6.2	0.1
Pro	7.7	8.8	7.1	7	7.2	0.3
Ser	6.7	7.1	5.6	5.5	5.7	0.1
Tyr	4.9	5.1	4.1	3.4	3.9	0.1

Table 3.7. Apparent ileal digestibility coefficients of crude protein and amino acids (AA) in five sources of full-fat soybeans (FFSB)[1]

Item	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	SEM	*P-value*	Average	SD[2]
Crude protein	0.76	0.81	0.81	0.81	0.81	0.02	0.163	0.80	0.02
Indispensable AA									
Arg	0.90[b]	0.92[a]	0.91[ab]	0.90[ab]	0.90[ab]	0.01	0.042	0.91	0.01
His	0.84	0.89	0.87	0.86	0.86	0.01	0.170	0.86	0.02
Ile	0.81	0.86	0.86	0.84	0.84	0.01	0.131	0.84	0.02
Leu	0.82	0.87	0.86	0.84	0.84	0.02	0.179	0.84	0.02
Lys	0.84	0.89	0.88	0.87	0.87	0.01	0.196	0.87	0.02
Met	0.81	0.87	0.84	0.83	0.83	0.02	0.223	0.84	0.02
Phe	0.82	0.87	0.86	0.84	0.84	0.01	0.114	0.85	0.02
Thr	0.73	0.79	0.76	0.75	0.74	0.02	0.136	0.75	0.02
Trp	0.81	0.85	0.85	0.86	0.83	0.02	0.275	0.84	0.02
Val	0.77	0.83	0.82	0.81	0.80	0.02	0.141	0.81	0.02
Dispensable AA									

Table 3.7 (cont.)

Ala	0.73	0.81	0.79	0.78	0.77	0.02	0.222	0.78	0.03
Asp	0.82	0.87	0.85	0.84	0.84	0.01	0.101	0.84	0.01
Cys	0.68[b]	0.78[a]	0.72[ab]	0.74[ab]	0.72[ab]	0.02	0.05	0.73	0.03
Glu	0.85[b]	0.90[a]	0.89[ab]	0.88[ab]	0.88[ab]	0.01	0.042	0.88	0.02
Gly	0.66[b]	0.76[a]	0.71[ab]	0.73[ab]	0.70[ab]	0.03	0.054	0.71	0.03
Pro	0.63	0.76	0.67	0.73	0.69	0.07	0.284	0.70	0.04
Ser	0.81	0.85	0.82	0.81	0.81	0.01	0.135	0.82	0.02
Tyr	0.81[ab]	0.85[a]	0.83[ab]	0.79[b]	0.79[b]	0.01	0.008	0.81	0.02

[a-b]Within a row, means without a common superscript differ ($P < 0.05$).

[1] Each least square mean represents 6 observations, except for FFSB source 01 (n = 5).

[2]The average and standard deviation is for the means.

Table 3.8. Standardized ileal digestibility coefficients (SID) coefficient of crude protein and amino acids (AA) in five different sources of full-fat soybean (FFSB)[1,2]

Item	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	SEM	*P-value*	Average	SD[3]
Crude protein	0.85	0.90	0.89	0.89	0.89	0.02	0.165	0.88	0.04
Indispensable AA									
Arg	0.94	0.96	0.96	0.95	0.95	0.01	0.089	0.95	0.02
His	0.87	0.92	0.92	0.90	0.90	0.01	0.205	0.90	0.04
Ile	0.85	0.90	0.89	0.88	0.87	0.01	0.165	0.88	0.03
Leu	0.85	0.90	0.89	0.88	0.87	0.02	0.203	0.88	0.04
Lys	0.87	0.91	0.91	0.91	0.90	0.01	0.219	0.90	0.03
Met	0.84	0.90	0.88	0.87	0.87	0.02	0.283	0.87	0.04
Phe	0.86	0.90	0.90	0.88	0.87	0.01	0.148	0.88	0.03
Thr	0.82	0.87	0.85	0.84	0.83	0.02	0.273	0.84	0.04
Trp	0.85	0.89	0.90	0.90	0.87	0.02	0.355	0.88	0.05
Val	0.82	0.88	0.87	0.86	0.85	0.02	0.182	0.85	0.04
Dispensable AA									
Ala	0.81	0.88	0.87	0.86	0.85	0.02	0.257	0.85	0.06
Asp	0.86	0.90	0.89	0.88	0.88	0.01	0.145	0.88	0.03
Cys	0.78	0.86	0.82	0.84	0.81	0.02	0.163	0.82	0.06
Glu	0.88[b]	0.92[a]	0.92[ab]	0.91[ab]	0.90[ab]	0.01	0.050	0.91	0.03
Gly	0.85	0.93	0.90	0.93	0.89	0.03	0.094	0.90	0.07

Table 3.8 (cont.)

Pro	1.12	1.18	1.19	1.26	1.21	0.07	0.237	1.19	0.17
Ser	0.87	0.90	0.89	0.88	0.88	0.01	0.314	0.89	0.03
Tyr	0.86	0.89	0.88	0.85	0.84	0.01	0.051	0.86	0.03

[1] Each least square mean represents 6 observations, except for FFSB source 01 (n = 5).

[2]Values for SID were calculated by correcting values for apparent ileal digestibility for basal ileal endogenous losses. The basal ileal endogenous losses were determined (g/kg dry matter intake) as CP,12.45; Arg, 0.49; His, 0.15; Ile, 0.29; Leu, 0.42; Lys, 0.31; Met, 0.06; Phe, 0.28; Thr, 0.52; Trp, 0.08; Val, 0.38; Ala, 0.50; Asp, 0.67; Cys, 0.22; Glu, 0.78; Gly, 1.27; Pro, 3.92; Ser, 0.43; Tyr, 0.21; and total AA, 10.99.

[3]The average and standard deviation is for the means.

[a-b] Within a row, means without a common superscript letter differ ($P < 0.05$).

Table 3.9. Concentration of standardized ileal digestible amino acids in sources of full-fat soybean (FFSB)[1, 2]

Item, g/kg	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	SEM	P-value	SD	Average
Crude protein	295.0	305.8	294.8	300.0	305.8	4.46	0.093	5.4	300.3
Indispensable AA									
Arg	23.7^{b}	24.3^{a}	23.0^{c}	24.2^{a}	24.1^{ab}	0.14	<0.001	0.5	23.9
His	8.5^{bc}	8.8^{a}	8.2^{c}	8.5^{b}	8.6^{ab}	0.07	<0.001	0.2	8.5
Ile	15.8^{ab}	16.4^{a}	15.5^{b}	15.7^{b}	15.5^{b}	0.18	0.008	0.4	15.8
Leu	24.2^{ab}	24.9^{a}	23.5^{b}	24.1^{ab}	23.9^{b}	0.26	0.008	0.5	24.1
Lys	20.8^{ab}	21.4^{a}	20.3^{b}	21.2^{a}	21.5^{a}	0.21	0.002	0.5	21.0
Met	4.1^{b}	4.4^{a}	4.0^{b}	4.4^{a}	4.4^{a}	0.05	<0.001	0.2	4.3
Phe	16.3^{ab}	16.7^{a}	15.8^{b}	15.9^{b}	16.0^{b}	0.17	0.004	0.4	16.1
Thr	11.2^{b}	12.1^{a}	11.4^{ab}	11.7^{ab}	11.6^{ab}	0.20	0.023	0.3	11.6
Trp	4.2^{ab}	4.0^{bc}	3.9^{c}	2.9^{d}	4.3^{a}	0.07	<0.001	0.6	3.8
Val	15.7^{ab}	16.2^{a}	15.1^{b}	15.6^{ab}	15.8^{ab}	0.22	0.013	0.4	15.7
Dispensable AA									
Ala	13.1^{ab}	13.6^{a}	12.8^{b}	13.2^{ab}	13.1^{ab}	0.22	0.016	0.3	13.1
Asp	34.4^{ab}	35.9^{a}	34.2^{b}	35.4^{ab}	35.3^{ab}	0.42	0.033	0.7	35.1
Cys	4.0^{b}	4.6^{a}	4.1^{b}	4.9^{a}	4.7^{a}	0.09	<0.001	0.4	4.5
Glu	55.3^{bc}	60.3^{a}	55.0^{c}	57.7^{b}	56.6^{bc}	0.58	<0.001	2.2	56.9
Gly	13.2^{b}	14.5^{a}	13.2^{b}	14.3^{ab}	13.8^{ab}	0.37	0.009	0.6	13.8
Pro	19.5	21.7	19.8	22.4	21.4	1.23	0.060	1.3	21.0

Table 3.9 (cont.)

Ser	12.3[b]	13.1[a]	12.8[ab]	12.9[a]	12.7[ab]	0.16	0.005	0.3	12.8
Tyr	10.6[a]	10.5[a]	10.0[b]	10.4[ab]	10.3[ab]	0.13	0.011	0.2	10.3

[1]Each least square mean represents 6 observations, except for FFSB source 01 (n = 5).

[2]All data presented on the basis of 880 g per kg dry matter.

[a-d]Within a row, means without a common superscript differ

LITERATURE CITED

Alonso, R., Aguirre, A., and Marzo, F., 2000. Effects of extrusion and traditional processing methods on antinutrients and in vitro digestibility of protein and starch in faba and kidney beans. Food Chem. 68, 159-165. doi:10.1016/S0308-8146(99)00169-7

AOAC Int., 2019. Official methods of analysis of AOAC Int. 21th ed. AOAC Int., Rockville, MD, USA.

AOCS., 2006. Official Methods and Recommended Practices of the AOCS. 5th ed. Am. Oil Chem. Soc., Champaign, IL, USA.

ASA. American Soybean Association., 2022. Soy stats: A reference guide to important soybean facts and figures. Soybean Assoc., USA: https://soygrowers.com/wp-content/uploads/2022/06/22ASA-002-Soy-Stats-Final-WEB.pdf. Accessed July, 2024.

Baker, K.M., Kim, B.G., and Stein, H.H., 2010. Amino acid digestibility in conventional, high-protein, or low-oligosaccharide varieties of full-fat soybeans and in soybean meal by weanling pigs. Anim. Feed Sci. Technol. 162, 66–73. doi:10.1016/j.anifeedsci.2010.08.012

Baker, K.M., Utterback, P.L., Parsons, C.M., and Stein, H.H., 2011. Nutritional value of soybean meal produced from conventional, high-protein, or low-oligosaccharide varieties of soybeans and fed to broiler chicks. Poult. Sci. 90, 390-395. doi:10.3382/ps.2010-00978

Basuchaudhuri, P., 2020. Physiology of Soybean Plant (1st ed.). CRC Press, Boca Raton, FL. Pages 9-10. doi:10.1201/9781003089124

Cervantes-Pahm, S.K., and Stein, H.H., 2008. Effect of dietary soybean oil and soybean protein concentration on the concentration of digestible amino acids in soybean products fed to growing pigs. J. Anim. Sci. 86, 1841–1849. doi:10.2527/jas.2007-0721

Cheng, Z., and Hardy, R.W., 2003. Effects of extrusion and expelling processing, and microbial phytase supplementation on apparent digestibility coefficients of nutrients in full-fat soybeans for rainbow trout (Oncorhynchus mykiss). Aquac. Res. 218, 501-514. doi:10.1016/S0044-8486(02)00458-1

Deng, J., Huang, X., Chen, J., Vanholme, B., Guo, J., He, Y., Qin, W., Zhang, J., Yang, W., and Liu, J., 2024. Shade stress triggers ethylene biosynthesis to accelerate soybean senescence and impede nitrogen remobilization. J. Plant Physiol. Biochem. 108658. doi:10.1016/j.plaphy.2024.108658

Ellis, R., Morris, E.R., and Philpot, C., 1977. Quantitative determination of phytate in the presence of high inorganic phosphate. Anal. Biochem. 77, 536-539. doi:10.1016/0003-2697(77)90269-X

Fanelli, N.S., Torres-Mendoza, L.J., Abelilla, J.J., and Stein, H.H., 2023. Chemical composition of banana meal and rice bran from Australia or South-East Asia. Anim. Biosci. 36, 1568-1577. doi:10.5713/ab.23.0071

Fouhse, J.M., Gao, J., Vasanthan, T., Izydorczyk, M., Beattie, A.D., and Zijlstra, R.T., 2016. Whole-grain fiber composition influences site of nutrient digestion, standardized ileal digestibility of amino acids, and whole-body energy utilization in grower pigs. J. Nutr. 147, 29–36. doi:10.3945/jn.116.238667

Galkanda-Arachchige, H.S.C., Stein, H.H., and Davis, D.A., 2021. Soybean meal sourced from Argentina, Brazil, China, India, and the USA as an ingredient in practical diets for Pacific white shrimp Litopenaeus vannamei. Aquacult. Nutr. 27, 1103-1113. doi:10.1111/anu.13251

Goebel, K.P., and Stein, H.H., 2011. Ileal digestibility of amino acids in conventional and low-Kunitz soybean products fed to weanling pigs. Asian-Australian J. Anim. Sci. 24, 88–95. doi:10.5713/ajas.2011.90583

González-Vega, J.C., Kim, B.G., Htoo, J.K., Lemme, A., and Stein, H.H., 2011. Amino acid digestibility in heated soybean meal fed to growing pigs. J. Anim. Sci. 89, 3617-3625. doi:10.2527/jas.2010-3465

Grant, G., 1989. Anti-nutritional effects of soybean: A review. Prog. Food Nutr. Sci. 13, 317-348. PMID: 2699045.

Grieshop, C.M., Kadzere, C.T., Clapper, G.M., Flickinger, E.A., Bauer, L.L., Fazier, R.L., and Fahey Jr, G.C., 2003. Chemical and nutritional characteristics of United States soybeans and soybean meal. J. Agric. Food Chem. 51, 7684-7691. doi:10.1021/jf034690c

Kaewtapee, C., and Mosenthin, R., 2024. Predicting standardized ileal digestibility of lysine in full-fat soybeans using chemical composition and physical characteristics. Anim Biosci. 37, 1077-1084. doi:10.5713/ab.23.0236

Kaewtapee, C., Eklund, M., Wiltafsky, M., Piepho, H.P., Mosenthin, R., and Rosenfelder, P., 2017. Influence of wet heating and autoclaving on chemical composition and standardized ileal crude protein and amino acid digestibility in full-fat soybeans for pigs. J Anim Sci. 95, 779–788. doi:10.2527/jas.2016.0932

Kiarie, G.E., Parenteau, I.A., Zhu, C., Ward, N.E., and Cowieson, A.J., 2020. Digestibility of amino acids, energy, and minerals in roasted full-fat soybean and expelled-extruded soybean meal fed to growing pigs without or with multienzyme supplement containing fiber-degrading enzymes, protease, and phytase. J. Anim. Sci. 98, skaa174. doi:10.1093/jas/skaa174

Kim, B., and Stein, H. H., 2009. A spreadsheet program for making a balanced Latin Square design. Rev. Colomb. Cienc. Pecu. 22, 591-596.

Kim, B.G., Kil, D.Y., Zhang, Y., and Stein, H.H., 2012. Concentrations of analyzed or reactive lysine, but not crude protein, may predict the concentration of digestible lysine in distillers dried grains with solubles fed to pigs. J. Anim. Sci. 90, 3798-3808. doi:10.2527/jas.2011-4692

Lagos, L.V., and Stein, H.H., 2017. Chemical composition and amino acid digestibility of soybean meal produced in the United States, China, Argentina, Brazil, or India. J. Anim. Sci. 95, 1626-1636. doi:10.2527/jas.2017.1440

Lee, S. A., Blavi, L., Navarro, D.M.D.L., and Stein, H.H., 2021. Addition of hydrogen chloride to collection bags or collection containers did not change basal endogenous losses or ileal digestibility of amino acid in corn, soybean meal, or wheat middlings fed to growing pigs. Anim. Biosci. 34, 1632–1642. doi:10.5713/ab.20.0838

Liener, I.E., 1981. Factors affecting the nutritional quality of soya products. J. Am. Oil Chem. Soc. 58, 406–415. doi:10.1007/BF02582390

Marty, B.J., Chávez, E. and De Lange, C.F.M., 1994. Recovery of amino acids at the distal ileum for determining apparent and true ileal amino acid digestibilities in growing pigs fed various heat-processed full-fat soybean products. J. Anim. Sci. 72, 2029–2037. doi:10.2527/1994.7282029x

Mertens, D.R., 2003. Challenges in measuring insoluble dietary fiber. J. Anim. Sci. 81, 3233-3249. doi:10.2527/2003.81123233x

Milani, N.C., De Paula, V.R.C., Azevedo, C.P.F., Sedano, A.A., Scarpim, L.B., Junior, H.M., Duarte, D.H.A., Carciofí, A.C., Neto, M.A. and Ruiz, U.S., 2022. Effects of extrusion on

ileal and total tract nutrient and energy digestibility of untoasted soybean meal in weanling pigs. Anim. Feed Sci. Technol. 284, 115206. doi:10.1016/j.anifeedsci.2022.115206

Navarro, D.M.D.L., Bruininx, E.M.A.M., de Jong, L., and Stein, H.H., 2018. Analysis for low-molecular weight carbohydrates are needed to account for all energy contributing nutrients in some feed ingredients, but physical characteristics do not predict in vitro digestibility of dry matter. J. Anim. Sci. 96, 532-544. doi:10.1093/jas/sky010

NRC., 2012. Nutrient requirements of swine: 11th revised edition. The National Academies Press, Washington, DC, USA.

Oliveira, M.S.F., Wiltafsky, M.K., Lee, S.A., Kwon, W.B., and Stein., H.H., 2020. Concentrations of digestible and metabolizable energy and amino acid digestibility by growing pigs may be reduced by autoclaving soybean meal. Anim. Feed Sci. Technol. 269, 114621. doi:10.1016/j.anifeedsci.2020.114621

Qin, G., Verstegen, M.W.A., and Van der Poel., A.F.B., 1998. Effect of temperature and time during steam treatment on the protein quality of full-fat soybeans from different origins. J. Sci. Food Agric. 77, 393-398. doi:10.1002/(SICI)10970010(199807)77:3%3C393::AID-JSFA59%3E3.0.CO;2-M

Ravindran, V., Abdollahi, M., and Bootwalla, S., 2014. Nutrient analysis, apparent metabolisable energy and ilea amino acid digestibility of full fat soybean for broilers. J. Anim. Sci. 197, 233-240. doi:10.1016/j.anifeedsci.2014.08.014

Rezaei, R., Wang, W., Wu, Z., Dai, Z., Wang, J., and Wu, G., 2013. Biochemical and Physiological Bases for Utilization of Dietary Amino Acids by Young Pigs. J. Anim. Sci. Biotechnol. 4, 7. doi:10.1186/2049-1891-4-7

Sanchez-Zannatta, J., Wang, L.F., Beltranena, E., Beattie, A.D., Newkirk, R.N., and Zijlstra, R.T., 2023. Diet nutrient digestibility and growth performance in weaned pigs fed barley differing in fermentable starch and fibre profile. Anim. Feed Sci. Technol. 295, 115550. doi:10.1016/j.anifeedsci.2022.115550

SAS Institute Inc., 2018. SAS/STAT®, User's Guide, Version 15.1., SAS Institute Inc., Cary, NC, USA.

Shurson, G.C., Hung, Y-T., Jang, J.C., and Urriola, P.E., 2021. Measures Matter—Determining the true nutri-physiological value of feed ingredients for swine. Animals. 11, 1259. doi:10.3390/ani11051259

Sotak-Peper, K.M., González-Vega, J.C., and Stein, H.H., 2017. Amino acid digestibility in soybean meal sourced from different regions of the United States and fed to pigs. J. Anim. Sci. 95, 771–778. doi:10.2527/jas.2016.0443

Stein, H.H., Sève, B., Fuller, M.F., Moughan, P.J., and de Lange. C.F.M., 2007. Invited review: Amino acid bioavailability and digestibility in pig feed ingredients: Terminology and application. J. Anim. Sci. 85, 172-180. doi:10.2527/jas.2005-742

Stein, H.H., Shipley, C.F., and Easter, R.A., 1998. Technical note: A technique for inserting a T-cannula into the distal ileum of pregnant sows. J. Anim. Sci. 76, 1433-1436. doi:10.2527/1998.7651433x

Tran, G., and Sauvant, D., 2004. Chemical data and nutritional value. In: A. Ponter, D. Sauvant, J.-M. Perez and G. Tran, editors, Tables of composition and nutritional value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses and fish. Wageningen Academic Publishers, Wageningen, the Netherlands. Pages 17-24.

Tukey, J.W., 1977. Exploratory data analysis. Boston, MA: Addison-Wesley Publisher.

USDA., 2023. United States Department of Agriculture. National Agricultural Statistics Service. https://www.nass.usda.gov/Data_and_Statistics/Citation_Request/index.php. Accessed April., 2024.

Waldroup, P.W., 1982. Whole soybeans for poultry feeds. Worlds Poult. Sci. J. 37, 28–35. doi:10.1017/WPS19820003

Wang, L., Zeng, Z., Hu, Q., Wang, L., Shi, H., Lai, C., and Zhang, S., 2023. Determination and prediction of the available energy and amino acids digestibility of full-fat soybean fed to growing pigs. J Anim Sci. 101, skac395. doi:10.1093/jas/skac395

Yáñez, J.L., Tofuko, T.A., Jha, R., Van Kempen, T.A.T.G., and Zijlstra, R.T., 2019. Nutrient digestibility of soybean products in grower-finisher pigs. J. Anim. Sci. 97, 4598–4607. doi:10.1093/jas/skz290

Yoon, J., and Stein, H.H., 2013. Energy concentration of high-protein, low-oligosaccharide, and conventional full fat de-hulled soybeans fed to growing pigs. Anim. Feed Sci. Technol. 184, 105-109. doi:10.1016/j.anifeedsci.2013.06.001

CHAPTER 4: DIGESTIBLE AND METABOLIZABLE ENERGY, AND STANDARDIZED TOTAL TRACT DIGESTIBILITY OF PHOSPHORUS IN FIVE SOURCES OF FULL-FAT SOYBEANS FED TO GROWING PIGS

ABSTRACT

Two experiments were conducted to test the hypothesis that there is no difference in the digestible energy (DE), the metabolizable energy (ME), and the standardized total tract digestibility (STTD) of P among five sources of full-fat soybeans (FFSB). The five sources of FFSB (source 01, 02, 03, 04, and 05) were collected from five different states in the United States and fed to growing pigs. In experiment 1, 48 pigs (initial body weight: 30.86 ± 1.64 kg) were placed in metabolism crates and allotted to six diets using a randomized complete block design with eight replicate pigs per diet. A basal diet based on corn as the only energy source and five diets containing corn and each source of FFSB were formulated. Pigs were fed experimental diets for 13 days and feces and urine were collected for four days. Results demonstrated that ME in corn was 15.73 MJ per kg dry matter (DM), and ME in the five sources of FFSB was 20.74, 19.85, 20.59, 20.19, and 21.22 MJ per kg DM, respectively. The ME in FFSB source 05 was greater ($P < 0.05$) than the ME in FFSB sources 02 and 04. There were no differences in DE:GE, ME:DE, or ME:GE among the five sources of FFSB or between FFSB and corn. In experiment 2, 80 pigs (initial body weight: 16.73 ± 3.16 kg) were housed in metabolism crates and allotted to a randomized complete block design with 10 diets and 8 replicate pigs per diet. Five diets contained each source of FFSB as the only source of P and five additional diets were formulated by adding 1000 phytase units (FTU)/kg of microbial phytase to the original five diets. Feces were collected from pigs for four days following five days of adaptation. Results demonstrated

that there were no interactions between use of phytase and source of FFSB, and no effects of use of phytase or source of FFSB were observed for feed intake, weight of feces excreted, or daily basal endogenous P loss. The STTD of P in the diet with FFSB source 05 was greater ($P < 0.05$) than the STTD of P in the other sources of FFSB if no phytase was used, but if phytase was added to the diets, no differences among the five sources of FFSB were observed (interaction, $P < 0.05$). However, the STTD of P was greater ($P < 0.05$) if phytase was used than if no phytase was used. In conclusion, results demonstrated that FFSB contained more ME than corn, but there were only minor differences among sources in ME. Likewise, the STTD of P in FFSB was not different among sources if microbial phytase was used.

Key words: digestibility, energy, full-fat soybean, phosphorus, pig

Abbreviations: ATTD, apparent total tract digestibility; EPL, endogenous phosphorus loss; FFSB, full-fat soybean; FTU, phytase units; DE, digestible energy; GE, gross energy; ME, metabolizable energy; SEM, standard error of the mean; STTD, standardized total tract digestibility; TIU, trypsin inhibitor.

INTRODUCTION

Whole soybeans, from which the oil is not extracted, are referred to as full-fat soybeans (FFSB) and may be used in diets for poultry and pigs because of it is high concentrations of protein, oil, linoleic acid, vitamin E, and lecithin (Ravindran et al., 2014). Full-fat soybeans contain approximately 180 to 200 g/kg oil (Marty et al., 1994; NRC 2012). Unprocessed raw soybeans, however, contain trypsin inhibitors that make them unsuitable to be included in diets for pigs and poultry, because trypsin inhibitors reduce feed efficiency due to reduced amino acid digestibility (Waldroup, 1982; Grant, 1989; Goebel and Stein, 2011). To inactivate trypsin

inhibitors, the soybeans need to be heated, which may be accomplished using an extruder. Energy is one of the most expensive components in diets for pigs and it is important to estimate the energy contribution from ingredients to formulate diets that meet requirements (Noblet, 2007). There is, however, a lack of information about the amount of digestible energy (DE) and metabolizable energy (ME) that pigs will obtain from FFSB, and it is also not known if the growing location affects DE and ME of FFSB.

As is the case for most plant ingredients, the majority of P in FFSB is bound to phytate, which is mostly indigestible by pigs (Zhai et al., 2022), but in most feed ingredients, it is possible to increase the digestibility of P by including microbial phytase in the diet (Pallauf et al., 1994; Lautrou et al., 2021). However, there is limited data demonstrating if microbial phytase also increases the digestibility of P in FFSB and it is uncertain if STTD of P is constant among sources of FFSB grown in different locations. Therefore, two experiments were conducted to test the null hypothesis that DE and ME and STTD of P in FFSB are not influenced by growing area and that STTD of P in FFSB is increased if microbial phytase is used.

MATERIALS AND METHODS

The protocols for two experiments were submitted to and approved by the Institutional Animal Care and Use Committee at the University of Illinois (Protocol nos.: 21247) prior to initiation of the experiments. Castrated male pigs that were the offspring of Line 800 boars mated to Camborough females (Pig Improvement Company, Hendersonville, TN, USA) were used in both experiments.

Soybeans were collected from five different states in the soybean growing area of the U.S. (i.e., Illinois, Pennsylvania, Iowa, North Dakota, and Ohio). The five sources of FFSB were processed in similar conditions and managed at the same facility with high-shear dry extruders

using two paired extruders (Model 2000, Insta-Pro® International, Grimes, IA). The two extruders each had a capacity of 1000 kg per hour and processing parameters were adjusted to maintain a minimum processing temperature of 160 o C. The extruded materials were cooled with ambient air using a rotary drum cooler (Model 900, Insta-Pro® International, Grimes, IA) to produce the final product of FFSB (Tables 4.1 and 4.2). The five sources of FFSB were randomly assigned the numbers 01, 02, 03, 04, or 05.

Diets and feeding

In experiment 1, a basal diet based on corn as the only energy source was formulated and five additional diets were formulated by mixing corn and each source of FFSB (Table 4.3). Thus, a total of six diets were used. Vitamins and minerals were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

In experiment 2, five diets containing each source of FFSB, and sucrose and cornstarch were formulated and, in each diet, the source of FFSB was the only source of P. Five additional diets were formulated by adding 1000 phytase units (FTU) per kg (Quantum Blue, AB Vista, Marlborough, UK) to each of the original five diets (Table 4.4). Vitamins and minerals other than P and Ca were included in all diets to meet or exceed the estimated nutrient requirements for growing pigs (NRC, 2012).

In both experiments, all diets were fed in meal form and pigs were limit fed at 3.2 times the energy requirement for maintenance (i.e., 197 kcal/kg × body weight0.60; NRC, 2012). Daily feed allowances were provided in two equal meals at 0800 and 1700 h. Throughout the experiments, pigs had free access to water.

Animal and housing

In experiment 1, 48 growing pigs (initial body weight: 30.86 ± 1.64 kg) were allotted to the six diets using a randomized complete block design with two blocks of 24 pigs and four pigs per diet in each block for a total of eight replicate pigs per diet. Pigs were housed individually in metabolism crates (0.81 × 2.59 m) that were equipped with a self-feeder, a bowl with a nipple waterer, and a slatted floor. A screen and a urine pan were placed under the slatted floor, which allowed for the total, but separate, collection of urine and fecal samples.

In experiment 2, 80 growing barrows (initial body weight: 16.73 ± 3.16 kg) were allotted to a randomized complete block design with 10 diets. There were two blocks of 40 pigs and four replicate pigs per diet in each block for a total of eight replicate pigs per diet. Pigs were placed in individual metabolism crates (0.69 × 0.86 m) that were equipped with a self-feeder, a nipple waterer, a slatted floor, and a screen placed under the slatted floor to allow for total collection of feces.

Sample collection

In experiment 1, feed consumption was recorded daily, and pigs were fed experimental diets for 13 d. The initial seven days were considered the adaptation period to the diet. Fecal samples were collected for four days according to the marker-to-marker approach (Adeola, 2001). Chromic oxide was the start marker that was included in the morning meal on day 8 and ferric oxide was the stop marker that was included in the morning meal on day 12. Collection of feces started when the start marker appeared in the feces and ceased when the stop marker appeared. Urine was collected in urine buckets over a preservative of 50 mL of 3 N HCL. Urine collection started at 0900 h on day 8 and ceased on day 12 at 0900 h. Fecal samples and 20% of the collected urine were stored at − 20 ºC immediately after collection.

In experiment 2, feed consumption was recorded daily, and diets were fed for 12 days. The initial five days were considered the adaptation period to the diet, whereas fecal materials were collected from the feed provided during the following four days using the marker-to-marker approach as in experiment 1. Fecal samples were stored at - 20 oC immediately after collection.

Chemical analysis

At the conclusion of both experiments, fecal samples were dried in a 50°C forced air drying oven, ground, mixed, and subsampled prior to analysis. Urine samples from experiment 1 were thawed and mixed within animal and diet, and a sub-sample was dripped onto cotton balls that were placed in a plastic bag and lyophilized before analysis (Kim et al., 2009).

Ingredient, diet, and fecal samples were analyzed for dry matter in both experiments (DM; method 930.15; AOAC Int., 2019). Diet, fecal, and urine from experiment 1 and ingredient samples were analyzed for gross energy (GE) using bomb calorimetry (Model 6400; Parr Instruments, Moline, IL, USA). Ingredient samples and diet samples from both experiments were also analyzed for ash (method 942.05; AOAC Int., 2019) and ingredients and diets samples from experiment 1 were analyzed for acid-hydrolyzed ether extract by acid hydrolysis using 3 N HCl (Ankom HCl Hydrolysis System, Ankom Technology, Macedon, NY, USA) followed by fat extraction (Ankom XT-15 Extractor, Ankom Technology, Macedon, NY, USA; method 2003.06; AOAC Int., 2019). Crude protein in ingredients and diets from experiment 1 were calculated as N × 6.25, and N was measured using the combustion procedure (Method 990.03; AOAC Int., 2019) on a LECO FP628 (LECO Corp., Saint Joseph, MI, USA). Ingredient samples were analyzed for insoluble dietary fiber and soluble dietary fiber according to method 991.43 (AOAC Int., 2019) using the Ankom Total Dietary Fiber Analyzer (Ankom Technology, Macedon, NY, USA). Total dietary fiber was calculated as the sum of insoluble and soluble dietary fiber.

Ingredients were also analyzed for sugars including glucose, fructose, maltose, sucrose, stachyose, raffinose, and verbascose using high-performance liquid chromatography (Dionex App Notes 21 and 92). Total starch was analyzed in the five sources of FFSB and in corn by the amyloglucosidase-alpha-amylase procedure corresponding to the enzymatically hydrolyzed starch converted to glucose, and analysis of glucose by spectrophotometry (method 996.11; AOAC Int., 2019). Trypsin inhibitor concentrations were analyzed in the five sources of FFSB (method Ba 12-75; AOCS, 2006). Concentrations of macro minerals and micro minerals in the five sources of FFSB, the concentration of P and Ca in diets from experiment 2, and the concentration of P in fecal samples from experiment 2 were analyzed by an inductively coupled plasma spectroscopy method (method 985.01 A, B, and C; AOAC, 2019) after wet ash sample preparation (method 975.03 B(b); AOAC Int., 2019). Phytic acid was also analyzed in FFSB samples (Ellis et al., 1977). Phytate-P was calculated by multiplying the analyzed phytate by 0.282 (Tran and Sauvant, 2004). Diets from experiment 2 were analyzed for phytase activity (method 2000.12; AOAC Int., 2019).

Calculations

In experiment 1, the apparent total tract digestibility (ATTD) of gross energy (GE) and dry matter was calculated for each diet, and DE and ME in each diet were calculated as well (NRC, 2012). The DE and ME in corn were calculated by dividing the DE and ME in the corn diet by the inclusion rate of corn in that diet (i.e., 968 g per kg) and the contribution of corn to the DE and ME in the corn-FFSB diets was calculated by multiplying the DE and ME in corn by the inclusion rate of corn in the corn-FFSB diets. This value was then subtracted from the DE and ME in the corn-FFSB diets to calculate the contribution from FFSB to the diets, and by

dividing by the inclusion rate of FFSB, values for DE and ME in each source of FFSB were calculated by difference (Adeola, 2001).

In experiment 2, the ATTD of P in each source of FFSB was calculated (NRC, 2012). By correcting this value for the basal endogenous loss of P (EPL; 190 mg per kg of dry matter intake; NRC, 2012), the STTD of P in each source of FFSB was calculated.

Statistical analyses

Homogeneity of the variances and normality were confirmed, and data were analyzed using the PROC MIXED in SAS (SAS Institute Inc., 2018). Outliers were identified as values that deviated from the predicted mean by more than two times the internally studentized residual within the treatment (Tukey, 1977). Mean values were calculated using the LSMeans statement and if the model was significant, means were separated using the PDIFF statement with Tukey's adjustment. Pig was the experimental unit, and results were considered significant at $P \leq 0.05$ and $0.05 \leq P < 0.10$ was considered a tendency. In experiment 1, diet was the fixed effect and block and replicate within block were random effects. In experiment 2, fixed effects included source of FFSB, phytase, and the interaction between FFSB and phytase, and block and replicate within block were random effects.

RESULTS

Pigs remained healthy during both experiments, no feed refusals were observed, and all pigs completed their assigned treatment. In experiment 1, one pig fed the corn diet was identified as an outlier during data analysis and this pig was removed from analysis. In Experiment 2, two pigs fed diets containing FFSB sources 01 and 02 and no phytase and two pigs fed diets

containing FFSB source 05 and no phytase were detected as outliers and removed from analysis. All other data were included in the final analysis.

FFSB sources

Concentrations of CP in FFSB source 03 (345.0g per kg) was less than CP in the other sources, with an average of the five sources of 358.8 g per kg, which is greater than in the corn used in this experiment. Acid hydrolyzed ether extract and insoluble dietary fiber, which on average were present in concentration of 182.4 and 187.2 g per kg, respectively, were also greater in FFSB than in corn. Gross energy was not different among the five sources of FFSB with an average of 22.6 ± 0.3 MJ per kg. The 5 sources of FFSB also contained sucrose, stachyose, and verbascose, where sucrose was in greater concentration than the other sugars and there was an average of 47.5 g stachyose per kg. Trypsin inhibitors in the FFSB were on average of 6.82 ± 0.76 TIU per mg. Phytic acid averaged 13.5 ± 1.1 g/kg, which corresponded to 3.8 ± 0.3 g per kg phytate-bound P; therefore, non-phytate bound P was on average 0.9 ± 0.2 g per kg. Calcium was greatest in FFSB source 03 (3.3 g per kg) and least in FFSB source 01 and 05 (2.1 g per kg), and K had an average of 14.1 g per kg of the five FFSB sources. The micromineral present at the greatest concentration was FE, which averaged 141 mg per kg among the five sources of FFSB.

Experiment 1, DE and ME in FFSB

Results indicated that feed intake was not different among diets, but GE intake of pigs fed the diets containing FFSB was greater ($P < 0.05$) compared with that of pigs fed the corn diet (Table 4.5). The weight of dry feces, fecal GE excretion, and urine weight were not different among treatments, but urine GE excretion was greater ($P < 0.05$) from pigs fed the diet containing FFSB source 04 than from pigs fed the corn diet. The ATTD of dry matter and GE

were not different among diets. The concentration of DE was greater ($P < 0.05$) in the diet containing FFSB source 05 than in diets containing FFSB sources 02, or 03, and ME was greater ($P < 0.05$) in the diet containing FFSB source 05 than in the diet containing source 03. However, all diets containing FFSB had DE and ME that were greater than the corn diet.

The DE and ME in all sources of FFSB were greater ($P < 0.05$) than in corn on an as-is and on a dry matter basis (Table 4.6). The DE (as-fed basis) of FFSB source 05 was greater ($P < 0.05$) than that of FFSB sources 02, 03, and 04. The ME (as-fed basis) in FFSB source 05 was also greater ($P < 0.05$) than in FFSB source 02. On a dry matter basis, DE in FFSB source 05 was greater ($P < 0.05$) than in FFSB source 02, and ME in FFSB source 05 was greater ($P < 0.05$) than in FFSB sources 02 and 04. There were no differences in DE:GE, ME:DE, or ME:GE among the five sources of FFSB or between FFSB and corn.

Experiment 2, STTD of P in FFSB

There were no interactions between use of phytase and FFSB for feed intake, daily basal endogenous P loss, or weight of feces (Table 4.7). No effects of use of phytase or source of FFSB were observed for weight of feces, but there was a tendency for a greater ($P < 0.10$) feed intake and EPL when phytase was used. There was no interaction between phytase and source of FFSB for P intake, ATTD of dry matter, or absorption of P, but P intake, ATTD of dry matter, and absorption of P were greater ($P < 0.05$) in pigs fed diets with phytase compared with pigs fed diets without phytase. Concentration of P in feces was greater ($P < 0.05$) in the diet containing FFSB source 04 without microbial phytase compared with pigs fed diets containing one of the other sources of FFSB, but the concentration of P in feces was not different among the five diets containing phytase with the exception that P in feces from pigs fed the diet containing FFSB source 04 was greater ($P < 0.05$) than in feces from pigs fed the diet with FFSB source 03

(interaction; $P < 0.05$). Fecal P output was less ($P < 0.05$) from pigs fed the diet containing FFSB source 05 without phytase compared with the other diets without phytase, but no difference was observed among sources if phytase was used (interaction; $P < 0.05$). The ATTD of P and STTD of P in the diet containing FFSB source 05 were greater ($P < 0.05$) compared with diets containing the other sources of FFSB without phytase, but there were no differences in the ATTD and STTD of P among sources of FFSB if phytase was used (interaction; $P < 0.05$). Concentration of P in feces and P output were greater ($P < 0.05$) in diets without phytase than in diets with phytase, but the ATTD of P and STTD of P were greater ($P < 0.05$) if phytase was used than if phytase was not used.

DISCUSSION

Full-fat soybean is a high-energy ingredient in swine diets, if FFSB is heat treated to inactivate trypsin inhibitors, FFSB contribute approximately 16.48 MJ of ME per kg (NRC, 2012), this is due to the high concentration of fat and protein (Kiarie et al., 2020; Wang et al., 2023a). Extrusion process of soybeans is the result of exposing soybeans to pressure and elevated temperatures and the primary objective of extruding FFSB is to inactivate the trypsin inhibitors and other antinutritional factors, but also reduce the content of water, which increasing the concentration of DM. However, the DM values observed in FFSB not variety compared with previous values (Cervantes-Pahm and Stein, 2008; Baker et al., 2010; Wang et al., 2023a). Extrusion process efficiency reduce trypsin inhibitors in the FFSB to be around 3 to 4.5 TIU per mg (Baker et al., 2010; Kiarie et al., 2020; Wang et al., 2023a), which is higher that values observed in this work (i.e. 5.7 to 7.7 TIU per mg DM basis). Energy composition, total dietary fiber, fat, and ash in FFSB were within the range verified in studies that evaluated FFSB,

whereas crude protein and fat were less than previously studies (NRC, 2012; Yoon and Stein, 2013; Wang et al., 2023b). Concentration of sugars were very low in corn, but as expected, FFSB contained sucrose, stachyose, and raffinose. Oligosaccharides in FFSB may decrease the digestibility of energy and reduce growth rate of weanling pigs whereas pigs older than 6 to 7 weeks are expected to be able to ferment the oligosaccharides (Baker et al., 2011; Yoon and Stein, 2013), which may increase digestibility of energy and nutrients. Full-fat soybean is a high-energy ingredient in swine diets, if FFSB is heat treated to inactivate trypsin inhibitors, FFSB contribute approximately 16.48 MJ of ME per kg (NRC, 2012), this is due to the high concentration of fat and protein (Kiarie et al., 2020; Wang et al., 2023a). Extrusion process of soybeans is the result of exposing soybeans to pressure and elevated temperatures and the primary objective of extruding FFSB is to inactivate the trypsin inhibitors and other antinutritional factors, but also reduce the content of water, which increasing the concentration of DM. However, the DM values observed in FFSB not variety compared with previous values (Cervantes-Pahm and Stein, 2008; Baker et al., 2010; Wang et al., 2023a). Extrusion process efficiency reduce trypsin inhibitors in the FFSB to be around 3 to 4.5 TIU per mg (Baker et al., 2010; Kiarie et al., 2020; Wang et al., 2023a), which is higher that values observed in this work (i.e. 5.7 to 7.7 TIU per mg DM basis). Energy composition, total dietary fiber, fat, and ash in FFSB were within the range verified in studies that evaluated FFSB, whereas crude protein and fat were less than previously studies (NRC, 2012; Yoon and Stein, 2013; Wang et al., 2023b). Concentration of sugars were very low in corn, but as expected, FFSB contained sucrose, stachyose, and raffinose. Oligosaccharides in FFSB may decrease the digestibility of energy and reduce growth rate of weanling pigs whereas pigs older than 6 to 7 weeks are expected to be able

to ferment the oligosaccharides (Baker et al., 2011; Yoon and Stein, 2013), which may increase digestibility of energy and nutrients.

Values for Ca and P in FFSB were lower than expected (Cheng and Hardy, 2003; NRC, 2012; Ravindra et al., 2014). In contrast, phytic acid, phytate-P, and the percentage of total P bound to phytate was greater than reported (Cheng and Hardy, 2003; NRC, 2012). High temperature used during extrusion, may reduce the concentration of phytic acid (Alonso et al., 2000; Milani et al., 2022), but the greater concentration of phytate-bound P that was observed in this experiment compared with previous experiments indicates that the extrusion did not likely reduce the amount of phytate bound P in the FFSB used in this research. The reduced Ca in the FFSB compared with values from previous experiments (Kiarie et al., 2020), is likely a result of differences among growing regions in soil mineral concentration, which may influence the composition of FFSB (Ohlrogge, 1960). Nevertheless, the majority of minerals analyzed in the FFSB utilized in the current experiments align with reported values (Cheng and Hardy, 2003; NRC, 2012; Kiarie et al., 2016).

The greater DE and ME in FFSB than in corn, is primarily a result of the high concentration of fat in FFSB and indicates that incorporation of FFSB in diets for pigs will increase diet ME because fat in FFSB has a high digestibility (Kim et al., 2013). The observation that the ratio between ME and DE was not different among the five sources of FFSB indicates that absorbed nutrients from all five sources were metabolized with the same efficiency and with the same efficiency as in corn. Therefore, FFSB may be beneficial in diets for weanling pigs and growing pigs where increased dietary energy usually results in increased growth performance and intestinal health (Li et at., 1990; Yang et at., 2023). Likewise, diets high in fat to lactating sows results in greater weaning weights of pigs due to greater fat and energy in milk (Tilton et al.,

1999). In contrast, FFSB in diets for finishing pigs may need to be restricted to reduce the risk of producing pigs with soft bellies, which results in inadequate bacon cutting and may result in enhanced rancidity (Leszczynski et al., 1992; Gatlin et al., 2002). The lack of a differences in the DE and ME among the five sources of FFSB confirmed the hypothesis that growing area does not influence the DE and ME of FFSB.

Total dietary fiber in the corn used in this experiment was greater and crude protein was less than previous values (NRC, 2012), and therefore, the GE was less than reported, which resulted in reduced DE and ME in the corn used in this experiment compared with reported values (NRC, 2012). The reduced acid hydrolyzed ether extract in the corn used for this experiment compared with most other values likely also contributed to the reduced DE and ME. The majority of GE in urine is N (Noblet et al., 1993), which is likely the reason for the increased gross energy in urine from pigs fed FFSB compared with pigs fed corn because crude protein in FFSB is greater than in corn.

Values for ATTD and STTD of P in FFSB calculated in this experiment were slightly greater than reported by NRC (2012) and also greater than in soybean meal (NRC, 2012). The reason for this observation may be that the high concentration of fat in FFSB reduces passage rate in the gastrointestinal tract, which provides more time for P digestion and absorption (Mateos et al., 1982; Paternostre et al., 2021). A greater STTD of P in FFSB compared with other ingredients has been reported previously (Liu et al., 2018).

Phosphorus is an essential nutrient that is required for bone development and other functions in the body (Palacios, 2006; Zhai et al., 2022). In plant feed ingredients such as FFSB, most P is bound to phytate, which is mostly indigestible by pigs because they do not synthesize adequate amounts of endogenous phytase to liberate P from phytate; therefore, P digestibility by

pigs in plant ingredients is low (Liao et al., 2005). However, use of microbial phytase improves digestibility of P because phytase hydrolyzes the ester bond between P and the inositol ring in phytate within the gastrointestinal tract of pigs (Pallauf et al., 1994; Lautrou et al., 2021; Zhai et al., 2022). In agreement with this, use of phytase in this experiment increased P digestibility as has been reported for other ingredients (Hong and Kim, 2021; Lee et al., 2021; Luciano et al., 2022). This was also in agreement with previous data with FFSB (Kiarie et al., 2020) and with soybean meal (Rojas and Stein, 2012; Sotak-Peper et al., 2016). In accordance with expectations, supplementation of phytase to the diets resulted in improvements in STTD and retention of P regardless of the source of FFSB, and the hypothesis that phytase increase P digestibility was, therefore, confirmed. As a consequence, excretion of P in feces was reduced by 50 to 60 percent when phytase was added to the diets. Therefore, use of phytase will result in reduced output of P from pigs fed diets containing FFSB. In addition, the increased STTD of P will result in a reduced need for feed phosphates in the diets.

CONCLUSION

Results demonstrated that phytate, minerals, and some macro nutrients varied slightly among the five sources of full-fat soybeans used. All sources of full-fat soybeans had greater metabolizable energy than corn, which indicates that the use of full-fat soybeans instead of soybean meal in corn-based diets results in increased digestible and metabolizable energy, which may be advantageous in diets for younger pigs and lactating sows. There were no differences in metabolizable energy among the five sources of full-fat soybeans used in the experiment indicating that the elevated energy concentration in diets containing full-fat soybeans will be obtained regardless of where in the United Stated the beans were grown. With the exception of

one source, no differences in standardized total tract digestibility of P among sources were observed. However, regardless of source, standardized total tract digestibility of P was greater if microbial phytase was added to the diet, and excretion of P in feces was reduced by 50 to 60 % when microbial phytase was added to diets containing full fat soybeans.

TABLES

Table 4.1. Analyzed nutrient composition and energy in corn and five sources of full-fat soybean (FFSB), as-is basis

Item		FFSB source						
	Corn	01	02	03	04	05	Average	SD
Dry matter, g/kg	880.6	937.1	934.7	920.4	941.8	936.1	934	7.2
GE, MJ/kg	15.8	23	22.4	22.2	22.5	22.9	22.6	0.3
Crude protein, g/kg	58.1	360.4	362.8	345	360	365.8	358.8	7.2
Total dietary fiber, g/kg	127.8	184	224	208	211	199	205.2	13.3
Soluble dietary fiber, g/kg	12	5	27	13	31	14	18	9.6
Insoluble dietary fiber, g/kg	115.8	179	197	195	180	185	187.2	7.5
Acid hydrolyzed ether extract, g/kg	34.7	189	181.4	176.5	179.3	186	182.4	4.5
Ash, g/kg	13.5	58.1	59	56.2	58.4	56.9	57.7	1
Sugar profile, g/kg								
Glucose	4.7	ND[a]	ND	ND	ND	ND	ND	ND
Maltose	1.2	ND	ND	ND	ND	ND	ND	ND
Fructose	7.8	ND	ND	ND	ND	ND	ND	ND
Sucrose	10.4	45.2	50.3	42.3	45.4	54.1	47.5	4.2
Stachyose	0.3	38.9	48.1	31.9	34.9	45.9	39.9	6.2
Raffinose	1.4	7.4	7.5	7.4	6.2	5.9	6.9	0.7
Verbascose	ND	2.6	4.7	3	2.5	3.5	3.3	0.8
Starch, g/kg	645	8.5	6.7	17.2	16.1	6.1	10.9	4.8

Table 4.1 (cont.)

Trypsin inhibitor, units per mg	ND	6.27	6.55	6.93	8.27	6.08	6.82	0.76

[a] ND: No detected.

Table 4.2. Analyzed mineral composition of five sources of full-fat soybeans (FFSB), as-is basis

Item, g/kg	FFSB source					Average	SD
	01	02	03	04	05		
Phytic acid	12.5	13.9	12.3	15.4	13.5	13.5	1.1
P	4.5	5.1	4.4	5.2	4.4	4.7	0.3
Phytate-P[a]	3.5	3.9	3.5	4.3	3.8	3.8	0.3
Phytate-P, g/kg total P	779.9	768.6	783	832	861.3	804.9	35.6
Nonphytate-P[b]	1.0	1.2	1.0	0.9	0.6	0.9	0.2
Ca	2.3	2.4	3.3	2.4	2.0	2.5	0.4
Mg	2.1	2.2	2.2	2.4	2.1	2.2	0.1
K	14.6	15.3	14.2	15.1	13.4	14.5	0.7
Na	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	< 0.3	0.0
S	3.1	3.5	3.1	4.1	3.5	3.5	0.4
Microminerals, mg/kg							
Cu	<23	<23	<23	<23	<23	<23	0.0
Fe	90	97	133	215	171	141.3	46.7
Mn	29	42	35	46	33	36.7	6.3
Zn	42	52	48	58	44	48.8	5.9

[a] Phytate-P was calculated by multiplying the analyzed phytic acid by 0.282 (Tran and Sauvant, 2004).

[b] Nonphytate-P was calculated as the difference between total P and phytate-P.

Table 4.3. Ingredient composition and analyzed nutrient composition of experimental diets, as-is basis (experiment 1)

Item	Corn	Full-fat soybeans sources				
		01	02	03	04	05
Ingredient, g/kg						
Ground corn	968.5	573.5	573.5	573.5	573.5	573.5
Full fat soybeans	-	400.0	400.0	400.0	400.0	400.0
Dicalcium phosphate	15.0	10.0	10.0	10.0	10.0	10.0
Ground limestone	7.5	7.5	7.5	7.5	7.5	7.5
Sodium chloride	4.0	4.0	4.0	4.0	4.0	4.0
Vitamin-mineral premix[a]	5.0	5.0	5.0	5.0	5.0	5.0
Analyzed nutrient composition						
Dry matter, g/kg	885.2	913.4	915.7	908.1	914.5	911.3
Gross energy, MJ/kg	15.4	18.3	18.2	18.1	18.1	18.3
Ash, g/kg	32.9	43.3	44.8	42.7	45.1	43.6
Crude protein, g/kg	58.7	171.7	175.4	174.5	173.5	174.2
Acid hydrolyzed ether extract, g/kg	20.4	81.8	74.5	79.2	85.2	91.8

[a] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D_3 as cholecalciferol, 1,660 IU; vitamin E as $_{DL}$-alpha-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamine mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin,

Table 4.3 (cont.)

0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydriodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

Table 4.4. Ingredient composition and analyzed nutrient composition of experimental diets, containing full-fat soybeans (FFSB) without or with microbial phytase, as-is basis (experiment 2).

Ingredient, g/kg	Without phytase					With phytase				
	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05
Corn starch	438.0	438.0	438.0	438.0	438.0	437.8	437.8	437.8	437.8	437.8
Full-fat soybeans	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0	450.0
Sucrose	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Ground limestone	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Sodium chloride	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
Vitamin-micromineral premix[a]	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
Phytase premix[b]	0.0	0.0	0.0	0.0	0.0	0.2	0.2	0.2	0.2	0.2
Analyzed values										
Dry matter, g/kg	946.1	948.1	939.9	944.8	947.9	947.1	947.6	936.8	943.6	941.7
Ash, g/kg	30.7	32.1	31.1	28.3	31.8	30.4	31.4	30.9	29.6	29.7
Ca, g/kg	1.9	1.9	2.0	2.1	1.8	2.2	2.2	2.8	2.0	1.8

Table 4.4 (cont.)

P, g/kg	2.2	2.3	2.0	2.4	2.2	2.2	2.3	2.1	2.4	2.2
Phytase, FTU[c]/kg	<70	<70	<70	<70	<70	1000	920	1100	1200	1100

[a] The vitamin-micromineral premix provided the following quantities of vitamins and micro minerals per kg of complete diet: vitamin A as retinyl acetate, 10,622 IU; vitamin D_3 as cholecalciferol, 1,660 IU; vitamin E as $_{DL}$-alpha-tocopheryl acetate, 66 IU; vitamin K as menadione nicotinamide bisulfate, 1.40 mg; thiamin as thiamine mononitrate, 1.08 mg; riboflavin, 6.49 mg; pyridoxine as pyridoxine hydrochloride, 0.98 mg; vitamin B_{12}, 0.03 mg; $_{D}$-pantothenic acid as $_{D}$-calcium pantothenate, 23.2 mg; niacin, 43.4 mg; folic acid, 1.56 mg; biotin, 0.44 mg; Cu, 20 mg as copper chloride; Fe, 123 mg as iron sulfate; I, 1.24 mg as ethylenediamine dihydriodide; Mn, 59.4 mg as manganese hydroxychloride; Se, 0.27 mg as sodium selenite and selenium yeast; and Zn, 124.7 mg as zinc hydroxychloride.

[b] The phytase premix (Quantum Blue 5000; AB Vista, Marlborough, UK) contained 5000 phytase units per gram. At 0.2 g per kg inclusion, the premix provided 1000 units of phytase per kg of complete diet.

[c] FTU = phytase units.

Table 4.5. Apparent total tract digestibility (ATTD) of dry matter and gross energy (GE) and values for digestible energy and metabolizable energy in experimental diets (Experiment 1) [1]

Item	Corn	Full-fat soybean sources					SEM	*P*-value	Average	SD
		01	02	03	04	05				
Intake										
Diet, kg/day	1.31	1.33	1.36	1.37	1.36	1.36	0.04	0.815	1.36	0.01
GE, MJ/day	20.07[b]	24.34[a]	24.69[a]	24.79[a]	24.72[a]	25.01[a]	0.59	<0.001	24.71	0.21
Fecal excretion										
Dry feces output, kg/day	0.12	0.14	0.15	0.14	0.14	0.13	0.01	0.126	0.14	0.01
GE, MJ/day	2.32	2.70	2.91	2.75	2.67	2.57	0.14	0.103	2.73	0.11
Urine excretion										
Urine output, kg/day	2.36	4.56	5.71	4.42	6.12	4.64	1.11	0.223	5.09	0.69
GE, MJ/day	0.35[b]	0.61[ab]	0.68[ab]	0.62[ab]	0.72[a]	0.69[ab]	0.08	0.033	0.67	0.05
ATTD of dry matter	0.901	0.895	0.889	0.894	0.898	0.903	0.004	0.122	0.896	0.005
ATTD of GE	0.885	0.888	0.882	0.888	0.891	0.897	0.005	0.277	889.8	0.005
Energy in diets, MJ/kg (as-is)										

Table 4.5 (cont.)

Digestible energy	13.62[c]	16.27[ab]	16.03[b]	16.12[b]	16.17[ab]	16.46[a]	0.08	<0.001	16.21	0.15
Metabolizable energy	13.34[c]	15.82[ab]	15.53[b]	15.67[ab]	15.63[ab]	15.95[a]	0.09	<0.001	15.72	0.15

[a-c] Within a row, means without a common superscript letter differ ($P < 0.05$).

[1] Each least squares mean is the mean of 8 observations, except for the diet containing corn ($n = 7$).

Table 4.6. Digestible energy (DE) and metabolizable energy (ME) in corn and five sources of full-fat soybeans (FFSB) [1, 2], exp. 1

Item	Corn	FFSB source					SEM	P-value	FFSB	
		01	02	03	04	05			SD	Average
As-is basis, MJ/kg										
DE	14.07[c]	20.52[ab]	19.90[b]	20.14[b]	20.25[b]	21.00[a]	0.17	<0.001	0.37	20.36
ME	13.78[c]	19.87[ab]	19.07[b]	19.42[ab]	19.33[ab]	20.13[a]	0.21	<0.001	0.37	19.54
Dry matter basis, MJ/kg										
DE	16.05[c]	21.53[ab]	20.74[b]	21.36[ab]	21.18[ab]	22.15[a]	0.19	<0.001	0.46	21.39
ME	15.73[c]	20.74[ab]	19.85[b]	20.59[ab]	20.19[b]	21.22[a]	0.23	<0.001	0.47	20.51
Digestibility and metabolizability										
DE:GE	0.887	0.893	0.884	0.909	0.899	0.915	0.08	0.052	0.011	0.900
ME:DE	0.980	0.964	0.958	0.964	0.954	0.959	0.007	0.183	0.004	0.960
ME:GE	0.869	0.861	0.847	0.876	0.858	0.877	0.009	0.206	0.011	0.864

[a-c] Within a row means without a common superscript letter differ ($P < 0.05$).

[1] Each least squares mean is the mean of 8 observations, except for the diet containing corn ($n = 7$).

[2] GE = gross energy.

Table 4.7. Effects of microbial phytase on apparent total tract digestibility (ATTD) and standardized total tract digestibility (STTD) of dry matter (DM) and P in five sources of full-fat soybeans (FFSB)[1], (experiment 2)

Items	No phytase					1000 units pf phytase per kg diet[2]					SEM	*P*-value		
	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05	FFSB 01	FFSB 02	FFSB 03	FFSB 04	FFSB 05		Phytase	FFSB	FFSB × Phytase
Feed intake, g/d	794	819	834	806	825	876	871	840	850	875	43.29	0.051	0.979	0.899
Fecal output, g/d	48	48	50	42	39	42	45	47	40	43	3.03	0.266	0.058	0.538
ATTD of DM, g/kg	0.939	0.943	0.940	0.948	0.954	0.952	0.949	0.944	0.953	0.951	0.003	0.011	0.008	0.212
P intake, g/d	1.71	1.88	1.69	1.96	1.80	1.88	2.00	1.70	2.06	1.91	0.10	0.049	0.002	0.904
P in feces, g/kg	19.0^{bc}	20.2^{b}	17.5^{c}	23.5^{a}	18.2^{bc}	9.4^{de}	9.9^{de}	8.7^{e}	11.4^{d}	9.7^{de}	0.90	< 0.001	< 0.001	0.020
P output, g/d	0.92^{a}	0.95^{a}	0.87^{ab}	0.98^{a}	0.72^{b}	0.39^{c}	0.44^{c}	0.40^{c}	0.45^{c}	0.42^{c}	0.06	< 0.001	0.005	0.033
P absorption, g/d	0.79	0.93	0.82	0.97	1.08	1.49	1.56	1.30	1.61	1.49	0.08	< 0.001	0.014	0.341
ATTD of P, g/kg	0.459^{c}	0.493^{c}	0.483^{c}	0.497^{c}	0.600^{b}	0.787^{a}	0.778^{a}	0.764^{a}	0.777^{a}	0.784^{a}	0.026	< 0.001	0.014	0.027
Basal EPL[3], mg/d	142.81	147.59	148.87	144.64	148.52	157.60	156.77	149.55	152.31	156.60	7.76	0.060	0.965	0.882

Table 4.7 (cont.)

STTD of P[4], g/kg	542.5[c]	572.0[c]	571.5[c]	570.6[c]	682.9[b]	870.5[a]	856.4[a]	851.7[a]	850.9[a]	865.7[a]	26.3	< 0.001	0.014	0.026

[a-b] Within a row, means without a common superscript differ (P < 0.05).

[1] Each least squares mean is the mean of 8 observations, except for diets containing FFSB source 01 without phytase (n = 7) and FFSB source 05 without phytase (n = 6).

[2] Phytase: Quantum Blue 5000 (ABvista, Marlborough, UK).

[3] EPL = endogenous P loss, this value was estimated to be 190 mg per kg of DM intake (NRC, 2012). The daily basal EPL (mg/d) for each diet was calculated by multiplying the EPL (mg per kg of the DM intake) by the daily DM intake of each diet.

[4] Values for STTD were calculated by correcting values for ATTD for basal endogenous losses (NRC, 2012).

LITERATURE CITED

Adeola, O., 2001. Digestion and balance techniques in pigs, In: Lewis, A.J., Southern, L.L. (Eds.), Swine Nutrition, CRC Press, Washington, DC, USA, pp. 903-916.

Alonso, R., Aguirre, A., and Marzo, F., 2000. Effects of extrusion and traditional processing methods on antinutrients and in vitro digestibility of protein and starch in faba and kidney beans. Food Chem. 68, 159-165. doi:10.1016/S0308-8146(99)00169-7

AOAC Int., 2019. Official methods of analysis of AOAC Int. 21th ed. AOAC Int., Rockville, MD, USA.

ASA. American Soybean Association, 2022. Soy stats: A reference guide to important soybean facts and figures. Soybean Assoc., USA. https://soygrowers.com/wp-content/uploads/2022/06/22ASA-002-Soy-Stats-Final-WEB.pdf. Accessed April, 2023.

Baker, K.M., Kim, B.G., and Stein, H.H., 2010. Amino acid digestibility in conventional, high-protein, or low-oligosaccharide varieties of full-fat soybeans and in soybean meal by weanling pigs. Anim. Feed Sci. Technol. 162, 66–73. doi:10.1016/j.anifeedsci.2010.08.012

Baker, K.M., Utterback, P.L., Parsons, C.M., and Stein, H.H., 2011. Nutritional value of soybean meal produced from conventional, high-protein, or low-oligosaccharide varieties of soybeans and fed to broiler chicks. Poult. Sci. 90, 390-395. doi:10.3382/ps.2010-00978

Cervantes-Pahm, S.K., and Stein, H.H., 2008. Effect of dietary soybean oil and soybean protein concentration on the concentration of digestible amino acids in soybean products fed to growing pigs. J. Anim. Sci. 86, 1841–1849. doi:10.2527/jas.2007-0721

Cheng, Z., and Hardy, R.W., 2003. Effects of extrusion and expelling processing, and microbial phytase supplementation on apparent digestibility coefficients of nutrients in full-fat

soybeans for rainbow trout (Oncorhynchus mykiss). Aquac. Res. 218, 501-514. doi:10.1016/S0044-8486(02)00458-1

Ellis, R., Morris, E.R., and Philpot, C., 1977. Quantitative determination of phytate in the presence of high inorganic phosphate. Anal. Biochem. 77, 536-539. doi:10.1016/0003-2697(77)90269-X

Gatlin, L.A., See M.T., Larick D.K., Lin X., Odle J., 2002. Conjugated linoleic acid in combination with supplemental dietary fat alters pork fat quality. J. Nutr. 132, 3105-3112. doi:10.1093/jn/131.10.3105

Goebel, K.P., and Stein, H.H., 2011. Ileal digestibility of amino acids in conventional and low-Kunitz soybean products fed to weanling pigs. Asian-Australian J. Anim. Sci. 24, 88–95. doi:10.5713/ajas.2011.90583

Grant, G., 1989. Anti-nutritional effects of soybean: A review. Prog. Food Nutr. Sci. 13, 317-348. PMID: 2699045.

Hong, B., and Kim, B.G., 2021. Supplemental phytase increases phosphorus digestibility in pigs regardless of phytase source or feed pelleting. Anim. Feed Sci. Technol. 276, 114901. doi:10.1016/j.anifeedsci.2021.114901

Kiarie, G.E., Parenteau, I.A., Zhu, C., Ward, N.E., and Cowieson, A.J., 2020. Digestibility of amino acids, energy, and minerals in roasted full-fat soybean and expelled-extruded soybean meal fed to growing pigs without or with multienzyme supplement containing fiber-degrading enzymes, protease, and phytase. J. Anim. Sci. 98, skaa174. doi:10.1093/jas/skaa174

Kiarie, E., Walsh, M.C., He, L., Velayudhan, D.E., Yin, Y.L., and Nyachoti, C.M., 2016. Phytase improved digestible protein, phosphorous, and energy contents in camelina expellers fed to growing pigs. J. Anim. Sci. 94, 215–218. doi:10.2527/jas.2015-9735

Kim, B.G., Petersen, G.I., Hinson, R.B., Allee, G.L., and Stein, H.H., 2009. Amino acid digestibility and energy concentration in a novel source of high-protein distillers dried grains and their effects on growth performance of pigs. J. Anim. Sci. 87, 4013–4021. doi:10.2527/jas.2009-2060

Kim, B. G., Kil D. Y., and Stein H.H., 2013. In growing pigs, the true ileal and total tract digestibility of acid hydrolyzed ether extract in extracted corn oil is greater than in intact sources of corn or soybean oil. J. Anim. Sci. 91:755-763. doi:10.2527/jas.2011-4777

Kim, H., Sung, J.Y., and Kim, B.G., 2022. The influence of protein concentrations in basal diet on metabolizable energy of full-fat soybeans and soy protein isolate determined by the difference procedure in pigs. Anim. Feed Sci. Technol. 288, 115299. doi:10.1016/j.anifeedsci.2022.115299

Lautrou, M., Narcy, A., Dourmad, J. Y., Pomar, C., Schmidely, P., and Montminy, MPL. 2021. Dietary phosphorus and calcium utilization in growing pigs: requirements and improvements. Front. Vet. Sci. 8, 734365. doi:10.3389/fvets.2021.734365

Lee, J., Kim, J.W., and Nyachoti, C.M., 2021. Standardized total tract digestibility of phosphorus in high-protein sunflower meal fed to growing pigs with or without phytase supplementation. Anim. Feed Sci. Technol. 274,114853. doi:10.1016/j.anifeedsci.2021.114853

Leszczynski, D.E., Pikul, J., Easter, R.A., McKeith, F.K., McLaren, D.G., Novakofski, J., Bechtel, P.J., and Jewell, D.E., 1992. Effect of feeding finishing pigs extruded full-fat

soybeans on performance and pork quality. J. Anim. Sci. 70, 2167–2174. doi:10.2527/1992.7072167x

Liao, S.F., Kies, A.K., Sauer, W.C., Zhang, M., Cervantes, Y.C., and He, J.M., 2005. Effect of phytase supplementation to a low- and a high-phytate diet for growing pigs on the digestibilities of crude protein, amino acids, and energy. J. Anim. Sci. 83, 2130-2136. doi:10.2527/2005.8392130x

Li, D.F., Thaler, R.C., Nelssen, J.L., Harmon, D.L., Allee, G.L., and Weeden, T.L., 1990. Effect of fat sources and combinations on starter pig performance, nutrient digestibility and intestinal morphology. J. Anim. Sci. 68, 3694–3704. doi:10.2527/1990.68113694x

Liu, J.B., Yan, H.L., Cao, S.C., Liu, J., and Zhang, H.F., 2018. Effect of feed intake level on the determination of apparent and standardized total tract digestibility of phosphorus for growing pigs. Anim. Feed Sci. Technol. 246, 233-240. doi:10.1016/j.anifeedsci.2018.10.012

Luciano, A., Espinosa, C.D., Pinotti, P., and Stein, H.H., 2022. Standardized total tract digestibility of phosphorus in bakery meal fed to pigs and effects of bakery meal on growth performance of weanling pigs. Anim. Feed Sci. Technol. 284, 115148. doi:10.1016/j.anifeedsci.2021.115148

Mateos, G.G., Sell, J.L., and Eastwood, J.A., 1982. Rate of food passage (transit time) as influenced by level of supplemental fat. Poult. Sci. 61, 94-100. doi:10.3382/ps.0610094

Marty, B.J., Chávez, E., and De Lange, C.F.M., 1994. Recovery of amino acids at the distal ileum for determining apparent and true ileal amino acid digestibilities in growing pigs fed various heat-processed full-fat soybean products. J. Anim. Sci. 72, 2029–2037. doi:10.2527/1994.7282029x

Milani, N.C., De Paula, V.R.C., Azevedo, C.P.F., Sedano, A.A., Scarpim, L.B., Junior, H.M., Duarte, D.H.A., Carciofí, A.C., Neto, M.A., and Ruiz, U.S., 2022. Effects of extrusion on ileal and total tract nutrient and energy digestibility of untoasted soybean meal in weanling pigs. Anim. Feed Sci. Technol. 284, 115206. doi:10.1016/j.anifeedsci.2022.115206

Noblet, J., Fortune, H., Dupire, C., and Dubois, S., 1993. Digestible, metabolizable and net energy values of 13 feedstuffs for growing pigs. Anim. Feed Sci. Technol. 42, 131–149. doi:10.1016/0377-8401(93)90029-J

Noblet, J., 2007. Net energy evaluation of feeds and determination of net energy requirements for pigs. Rev. Bras. Zootec. 36, 277–284. https://doi.org/10.1590/S1516-35982007001000025

NRC., 2012. Nutrient requirements of swine: 11th revised edition. The National Academies Press, Washington, DC, USA.

Ohlrogge, A.J., 1960. Mineral nutrition of soybeans. Adv. Agron. 12, 229-263. doi:10.1016/S0065-2113(08)60084-X

Palacios, C., 2006. The role of nutrients in bone health, from A to Z. Crit. Rev. Food Sci. 46, 621-628. doi:10.1080/10408390500466174

Pallauf, J., Rimbach, G., Pippig, S., Schindler, B., Höhler, D., and Most, E., 1994. Dietary effect of phytogenic phytase and an addition of microbial phytase to a diet based on field beans, wheat, peas and barley on the utilization of phosphorus, calcium, magnesium, zinc and protein in piglets. Eur. J. Nutr. 33, 128-135. doi:10.1007/bf01622225

Paternostre, L., De Boever, J., and Millet, S., 2021. Interaction between fat and fiber level on nutrient digestibility of pig feed. Anim. Feed Sci. Technol. 282, 115126. doi:10.1016/j.anifeedsci.2021.115126

Ravindran, V., Abdollahi, M., and Bootwalla, S., 2014. Nutrient analysis, apparent metabolisable energy and ilea amino acid digestibility of full fat soybean for broilers. J. Anim. Sci. 197, 233-240. doi:10.1016/j.anifeedsci.2014.08.014

Rojas, O. J., and Stein, H. H., 2012. Digestibility of phosphorus by weanling pigs of fermented and conventional soybean meal without and with microbial phytase. J. Anim. Sci. 90, 1506–1512. doi:10.2527/jas.2011-4103

SAS Institute Inc., 2018. SAS/STAT®, User's Guide, Version 15.1., SAS Institute Inc., Cary, NC, USA.

Sotak-Peper, K.M., González-Vega, J.C., and Stein, H.H., 2016. Effects of production area and microbial phytase on the apparent and standardized total tract digestibility of phosphorus in soybean meal fed to growing pigs. J. Anim. Sci. 94, 2397-2402. doi:10.2527/jas.20160353

Tilton, S.L., Miller, P.S., Lewis, A.J., Reese, D.E., and Ermer, P.M., 1999. Addition of fat to the diets of lactating sows: I. Effects on milk production and composition and carcass composition of the litter at weaning. J. Anim. Sci. 77, 2491–2500. doi:10.2527/1999.7792491x

Tran, G., and Sauvant, D., 2004. Chemical data and nutritional value. In: A. Ponter, D. Sauvant, J.-M. Perez and G. Tran, editors, Tables of composition and nutritional value of feed materials: pigs, poultry, cattle, sheep, goats, rabbits, horses and fish. Wageningen

Academic Publishers, Wageningen, the Netherlands. pp. 17-24. doi:10.3920/978-90-8686-668-7

Tukey, J.W., 1977. Exploratory data analysis. Boston, MA: Addison-Wesley Publisher.

Waldroup, P.W., 1982. Whole soybeans for poultry feeds. Worlds Poult. Sci. J. 37, 28–35. doi:10.1017/WPS19820003

Wang, L., Zeng, Z., Hu, Q., Wang, L., Shi, H., Lai, C., and Zhang, S. 2023a. Determination and prediction of the available energy and amino acids digestibility of full-fat soybean fed to growing pigs. J Anim Sci. 101, skac395. doi:10.1093/jas/skac395

Wang, Y., Li, G., Ma, X., Xu, S., Lin, Y., Hua, L., Li, J., Feng, B., Fang, Z., Jiang, X., Zhuo, Y., Che, L., and Wu, D. 2023b. Chemical composition, energy content and apparent total tract digestibility of extruded full fat soybean from different sources fed to non-gestating, gestating and lactating sows. J. Anim. Sci. 101:skad154. doi:10.1093/jas/skad154

Yang, W., Jiang, F., Yu, B., Huang, Z., Luo, Y., Wu, A., Zheng, P., Mao, X., Yu, J., Luo, J., Yan, H., and He, J., 2023. Effect of different dietary lipid sources on growth performance, nutrient digestibility, and intestinal health in weaned pigs. Animals. 13, 3006. doi:10.3390/ani13193006

Yoon, J., and Stein, H.H., 2013. Energy concentration of high-protein, low-oligosaccharide, and conventional full fat de-hulled soybeans fed to growing pigs. Anim. Feed Sci. Technol. 184, 105-109. https://doi.org/10.1016/j.anifeedsci.2013.06.001

Zhai, H., Adeola O., and Liu, J., 2022. Phosphorus nutrition of growing pigs. Anim. Nutr. 9, 127-137. doi:10.1016/j.aninu.2022.01.010

CHAPTER 5: GENERAL CONCLUSIONS

The chemical composition of five sources of full-fat soybeans (FFSB) was consistent regardless of where they were grown. The extrusion process used to prepare the FFSB was effective in reducing the concentration of trypsin inhibitor units. Full-fat soybeans contained more metabolizable energy than corn, but there were only minor differences among the five sources of FFSB in metabolizable energy. Likewise, the standardized total tract digestibility (STTD) of P in FFSB was not different among sources if microbial phytase was used. The addition of exogenous microbial phytase positively influenced the apparent ileal digestibility of P and the STTD of P in FFSB, indicating that less inorganic phosphorus would be required when microbial phytase is included in the diets. The standardized ileal digestibility of amino acids indicated that all five sources of FFSB had high digestibility and although minor differences among the five sources were observed, it was concluded that FFSB from all five sources may be used in diets for growing pigs. Further research should be conducted to evaluate growth performance and gut health when FFSB is fed to pigs.

The data generated from this research may be used to formulate diets for pigs with FSBM and mixed with cereal grains, based on additive digestibility values of ME, SID of AA, and STTD of P. Data may also be used to formulate diets in future experiments to evaluate performance and determine the maximum inclusion rate when FFSB is fed to growing and finishing pigs, as well as gestating and lactating sows.