ABSTRACT

ALI, MUHAMMAD. Effects of High Oleic Full-Fat Soybean on Live Performance, Carcass and Meat Quality, Meat Fatty Acid Composition, AMEn and Amino Acid SID in Broilers. (Under the direction of Dr. Edgar O. Oviedo Rondon).

Soybeans are an ideal protein for broiler diets due to their good amino acid profile. It is also a source of energy. Before its inclusion in broiler diets, it is essential to process it, and for this purpose, different processing methods are used. In the late nineteens, scientists genetically modified normal oleic soybean to increase its oleic acid content, thus producing a variety generally known as high oleic soybean. It has three times more oleic acid content at the expense of linoleic and linolenic acid content. High oleic soybean oil has more shelf life and is considered better for human health due to its antioxidant properties and high oleic acid content. While high oleic soybean is considered suitable for human consumption, it also may positively influence broiler meat quality. This study used high oleic soybean to evaluate its effect on liver performance, carcass and meat quality, meat fatty acid composition, standardized ileal amino acid digestibility, and apparent metabolizable energy corrected by nitrogen in broilers. The first chapter presents a literature review of high oleic soybean, its nutritional values, anti-nutritional factors, limitations, processing, and quality control methods. The study in the second chapter evaluates the effect of different soybean sources; normal oleic extruded expeller (NO-EE), normal oleic full-fat (NO-FF), and high oleic full-fat (HO-FF) soybean on liver performance, carcass, and meat quality and meat fatty acid composition of broilers. Although the live performance of broilers fed on HO-FF soybean diets was lower than the other two groups, they had a significantly high quantity of oleic acid in their breast meat. Linoleic, palmitic, and stearic acids were reduced in the breast muscles of broilers fed on HO-FF soybean diets. In the third chapter, apparent ileal and standardized ileal amino acid (AA) digestibility of HO-FF soybeans was analyzed compared to solvent-extracted

soybean meal (SE SBM), NO-EE, and NO-FF soybeans in broilers. A nitrogen-free diet (NFD) was formulated to feed one group, and titanium dioxide was used as an inert marker while basal endogenous losses (BEL) were also calculated. Although AA's apparent and standardized ileal digestibility were nearly similar for HO-FF and NO-FF, HO-FF has significantly lower values than SE-SBM and NO-EE soybean.

The highest values were observed for SE SBM. In the fourth experiment, apparent metabolizable energy (AME) and AME corrected by nitrogen (AMEn) were calculated for HO-FF soybean compared to SE SBM, NO-EE, and NO-FF soybeans in broilers. A basal energy diet and titanium dioxide as inert marker were used in this experiment. The energy values were calculated by both partial and total excreta collection methods. In both methods, the highest AME and AMEn were observed for the HO-FF soybean, while SE SBM had the lowest values. The results of all experiments show that HO-FF is a valuable feed ingredient to be used in broiler diets. If properly processed, it can replace other soybean sources and enrich broiler meat with a high oleic acid content, which can ultimately be good for human consumption and health.

Effects of High Oleic Full-Fat Soybean on Live Performance, Carcass and Meat Quality, Meat Fatty Acid Composition, AMEn and Amino Acid SID in Broilers

by
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DEDICATION

To my beloved grandparents and parents for their continuous guidance and countless prayers.

To my brother and sister, for their love and being there whenever I need them.

To my wife and daughter for their moral support and motivation from the start until now.

Finally, I dedicate this work to Justina Caldas (Ph.D.), a very kind human being and committed poultry nutritionist, for her guidance and mentorship every time it was needed and to all those brilliant scientists working tirelessly around the globe for the betterment of humankind and the planet.

BIOGRAPHY

Muhammad Ali is a veterinarian with particular emphasis and expertise in poultry nutrition and production. He got his veterinary medicine degree from the University of Veterinary and Animal Sciences, Lahore (Pakistan). After obtaining his degree, he got excellent and broad experience in technical sales and services spanning multiple years in different commercial poultry feed companies. He started his job with a large-scale national poultry group from the root level to eventually move to the upper ladder, and his last assignment was in Pakistan with Charoen Pokphand Group, the world's largest animal feed manufacturer. He was awarded various honors and scholarships throughout his academic and professional journey. He traveled nationally and internationally to participate in training courses and seminars in poultry, computer, leadership, and management. After that, he got the opportunity to pursue his master’s in poultry science and nutrition from North Carolina State University, Raleigh. He started his master’s degree in January 2021 to start research on the usage of high oleic full-fat soybeans in broiler diets, and this study was the first of its kind globally. His strong technical and managerial skills have prepared him to utilize his academic knowledge and practical experience for the betterment of the poultry industry as a veterinarian and nutritionist.

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CHAPTER 1

High oleic full-fat soybean, its uses, and limitations in poultry diet: A review

Abstract

On a global scale, the poultry industry expands its wings regarding meat and egg provision to the masses. But this industry requires a sustainable and permanent supply of different inputs, one of which is poultry nutrition. Soybean is a versatile protein offered to poultry in different inclusion rates in diets and after being processed by various techniques. It is used in poultry diets as a source of protein and energy. Scientists produced a soybean variety with high oleic fatty acid content than commercially available soybean in the late nineteens. High oleic soybeans have three times more oleic acid than normal oleic soybean, while linoleic and linolenic acid content was reduced in high oleic varieties. High oleic soybean oil has a longer shelf life and more advantages than normal oleic or other commodity oils when supplementing natural antioxidants. Soybean meal (SBM) is usually prepared by the solvent extraction process of soybeans, and almost all oil content is removed. When oil is not extracted from it, it is referred to as full-fat Soybean (FFSB), an excellent source of energy for poultry. Using the FFSB, the cost of mixing the other vegetable oils can be saved when economically feasible. However, some antinutritional factors (ANF) will be present in FFSB if not heat-treated before mixing in feed. These ANFs affect the growth of avian species and internal organs. Among these factors, trypsin inhibitors (TI) are the most important, but these are easily destroyed by heat treatment. But during heat treatment, it should be kept in mind that optimum heating is essential for adequately processing FFSB; otherwise, under-processing will result in the presence of ANFs, while over-processing will destroy or create a complex with the amino acids (AA), especially Lysine. Some ANF, other than TI, can also be present in soybeans which can be heat resistant, so there is a growing trend of adding enzyme supplementations in diets while watching the economic aspect. Quality of processing can be checked *in vitro* by different lab tests, including Nitrogen Solubility Index (NSI), Protein Dispersibility Index (PDI), Urease Activity (UA), and Protein Solubility in Potassium Hydroxide (KOHPS), etc. Once properly processed, high oleic full-fat (HO-FF) soybean can be used safely in the broiler, layer, turkey, and duck feed at different inclusion rates. It may result in economic viability, better growth rate, and feed conversion ratio (FCR). Also, feeding HO-FF soybean can change chickens' meat fatty acid composition, including increasing the oleic acid content. It can help enrich meat composition, ultimately benefiting human health, especially cardiovascular well-being.

Keywords: High oleic soybean, full-fat soybean, broilers, quality parameters, soybean meal.

Introduction

The soybean (*Glycine max*) is considered one of the most important oilseed crops in the world, and its seeds provide almost 60% of the world's supply of vegetable protein and 30% of oil (Uhegbu *et al*., 2013). In 2021, soybean production in the US was recorded at 4.44 billion bushels (USDA, 2022). As a source of protein and oil, its use has been extended around the globe (El-Shemy, 2011). Although deficient in Na and Vitamin C, it contains sufficient amounts of Vitamin B_1, B_2, and K (Căpriţă *et al*., 2010b; Lázaro *et al*., 2006) and is an excellent source of high-quality protein often utilized in animal feed industry. In 1917, Osborne and Mendel established a reasonable growth rate by adding soybeans to animal feed if heated properly before inclusion. Initially, the efforts to include the soybean in animal diets were unsuccessful due to growth retardation compared to those fed on other protein sources. After that, it was observed that heating denatured the protease inhibitors, which were responsible for growth retardation. Feed manufacturers use soybean meal (SBM) as a standard against which other plant protein sources are compared (Willis, 2003).

Generally, soybean has 160 – 210g/kg of oil; with solvent extraction, the SBM has an oil portion of just 10 g/kg. This meal is considered an excellent source of high-quality protein in poultry as it contains all essential amino acids (AA) in amounts needed for maximum growth, except cysteine and methionine, which are suboptimal (McDonald *et al*., 2008). The full-fat soybeans (FFSB) contain a good profile of essential AA and are a good energy source. On average, it has 38-40% protein and 18-20% lipid as energy (Reddy and Bhosale, 2001). When FFSB is compared with solvent-extracted (SE) SBM, it is evident that FFSB has lower crude protein (CP) than SE SBM with greater metabolizable energy (ME) due to higher fat and energy content. The FFSB has more crude fiber but fewer minerals (phosphorus and calcium) than SE SBM (Willis, 2003) (Table 1).

There is a specific requirement of essential AA for chickens which must be available in the diet. Ideal protein meets this dietary requirement by proving the quantity of quality AA. The FFSB has an ideal balanced profile of AAs; however, there is a deficiency of methionine, but synthetic methionine dietary supplementation is utilized to fulfill this deficiency (Tables 3 and 4).

Generally, carbohydrate content in soybean ranges from 30 – 35%, while in SBM, it is around 40% (NRC, 1994). These carbohydrates can be nonstructural, including low molecular weight sugars, oligosaccharides, and storage polysaccharides (Karr-Lilienthal et al., 2005). They can be structural polysaccharides and include dietary fiber components (Bach Knudsen *et al.*, 1987). Galacto-oligosaccharides (raffinose, stachyose, and verbascose) comprise almost 5% of the dry soybean matter, while starch represents less than 1% (Karr-Lilienthal *et al.*, 2005). FFSB has a high content of oil as compared to soybean meal. Soybean oil is 61% polyunsaturated fat and 24% monounsaturated fat. It does not have cholesterol or trans fat but is high in poly and monounsaturated fat (Uhegbu *et al.*, 2013). Supposing the high degree of unsaturation of oil, the dietary energy content will also be high because unsaturated oil contains one or more double or triple bonds between its molecules. Generally, conventional normal-oleic soybean oil includes 250 g of oleic acid/kg, while linoleic acid, an essential fatty acid for poultry, with 500 g/kg, is almost double it (Wiseman, 1994) (Table 5).

Changing the fatty acid composition of chicken meat can change the pace of lipid oxidation within fresh chicken meat. An elevated level of polyunsaturated fatty acids can produce "soft fat" (Mir *et al.*, 2017), making it more vulnerable to lipid oxidation. Due to it, the shelf-life of fresh poultry meat can be lessened. In a study conducted by Zollitsch *et al*. (1997), it was concluded that the fatty acid profile of abdominal fat pads and thigh meat showed the fatty acid profile of the corresponding diet given to the chickens. For example, when beef tallow was replaced with olive oil in the broilers diet, there was a significant increase in monounsaturated fatty acid content in the breast meat of the broiler, especially oleic fatty acid. Olive oil has a similar fatty acid profile to high oleic soybean. This increase in monounsaturated fatty acids was at the expense of a decreased level of saturated fatty acids (Hsieh *et al*., 2002).

In developed nations, meat consumers have a greater interest in extrinsic factors of food, such as meat quality, instead of price (FAO, 2013). The use of niche, health-focused markets, and labeling may offer a premium price on poultry meat enriched with good fatty acids for human health. The cost of "Whole Omega-3 Roaster" chicken sold by the Texas-based company Slanker Grass-Fed Meat is $6.99 per pound (Slanker Grass-Fed Meat, N.D), while commodity whole roaster chicken is sold at $1.39 per pound (USDA, 2020). The more gain in profit through niche premium markets focused on health-conscious customers may be a better option for marketing chicken meat fed on high oleic soybean oil (Peckman, 2020).

Quality is a significant parameter during the processing and storage of chicken meat. Most of the time, this issue is not very important; however, sometimes, FFSB in poultry diets should be checked to meet the needs of poultry processors (Newkirk, 2010). Broilers fed on high oleic soybean meal and oil showed a 20 percent lower exposure of lipid oxidation byproduct malonaldehyde in boneless, skinless breast samples after five days of retail storage than those fed on conventional corn-soybean meal diets. This decrease in lipid oxidation can offer possible benefits to both vendors and buyers of poultry meat. Poultry meat products of approximately $ 15.4 billion were discarded by retailers and consumers, in 2010, due to overstocked shelves, spoilage, and undesirable product appearance (Buzby *et al*., 2014). Soybean also contains various vitamins and minerals, but different soybean products have different levels. For example, FFSB includes more vitamin E and thiamine than other products (Tables 6 and 7).

Limitations / Anti-Nutritional Factors

Raw soybean contains different antinutritional factors (ANF), which are inappropriate for poultry diets (Ravindran *et al*., 2014; Waldroup, 1982). The most critical factors are trypsin inhibitors (TI) and lectins (Ravindran *et al*., 2014; Liener, 1981; Grant, 1989). The two most crucial TI are Bowman-Birk Inhibitor and the Kunitz Inhibitor. These TI protect plants during germination from micro-organisms in the soil and airborne pests before the maturity of the seed; however, when chickens are fed unprocessed soybeans, there is a reduction in body weight and growth. Protease inhibitors present in unprocessed soybeans can interfere with digestive enzymes and negatively impact growth (Erdaw and Beyene, 2018). Pancreas weight also increases with the high level of TI activity (mg/g dry matter) in feed (Perilla *et al*., 1997). Raw soybean (on a dry matter basis) typically has a TI activity between 20 to 35 mg/g. The recommended maximum level of TI in soybean is 4 mg/g, which has a minimum adverse effect in chickens, but the ground for such a recommendation is unclear (Clarke & Wiseman, 2007). Due to the adverse action of TI on protein digestion and absorption, nitrogen (N) retention can have a negative impact, and hence the excretion of metabolic N (Erdaw *et al*., 2017).

Soybeans contain some other ANF, such as oligosaccharides, phytate, saponin, and lectins which can reduce growth and protein digestibility in chickens (Parsons *et al*., 2000; Palacios *et al*., 2004). Lectins or hemagglutinins are the compounds that can cause red blood cells to attach to each other (Koch, 2020). They can bind to glycoprotein receptors of the digestive tract wall, thus damaging its lining and reducing its performance (Liener, 1994). The anti-nutritional effects of lectins are basically due to their ability to impair the digestive tract wall, not due to binding the blood cells (Newkirk, 2010). Lectins are also made of protein and can be denatured by heat treatment (de Muelenaere, 1964).

Saponins are present in only small amounts in soybeans. They can induce a bitter taste and may affect nutrient absorption to some extent, but usually, their concentration is low enough not to be considered for practical significance (Ishaaya *et al*., 1969). Oligosaccharides in SBM may be responsible for poor performance in broilers. Their high concentrations in the small intestine can produce an osmotic effect resulting in the adverse effect of nutrient absorption (Choct *et al*., 2010). Higher levels of non-starch polysaccharides (NSP) can also decrease nutrient digestion and absorption in chickens (Antoniou *et al*., 1981).

Metal chelating factors present in soybeans may include interference with the availability of trace minerals, including zinc, manganese, copper, and iron (Koch, 2020). Methionine is a limiting AA in soybean, and this issue is solved by supplementing the diet with synthetic methionine (Waldroup and Smith, 2008). Methionine supplementation becomes more valuable in diets containing unprocessed or incompletely processed soybean than in diets containing properly processed beans (Ogundipe *et al*., 1974), but giving methionine supplementation will not compensate for the reduction in growth affected by raw soybean. Overall, soybean lacks sulfur-containing AAs, and the presence of anti-trypsin factors will further decrease this AA's existence (Lázaro *et al*., 2006).

Processing

FFSB is an excellent source of protein as well as oil. But if not processed properly, it may contain ANF and exhibit different disadvantages to chickens regarding growth and digestibility. The common objective of processing is to denature the heat-labile ANF, and most of the time, the processing involves different variables, including temperature, moisture, and time. The critical part to remember is that processing is beneficial for denaturing ANF. Still, if it is done excessively, it can affect the nutritional profile of soybean and can reduce the AA contents. So, an ideal processing method will destroy the ANF but, at the same time, will keep the AA profile intact.

Protease inhibitors (trypsin and chymotrypsin inhibitors), lipoxygenase, allergenic proteins, and hemagglutinins (or lectins) are considered heat-labile anti-nutrients. Still, the latter two are slightly more resistant to heat than others (Swick, 2020).

Heat treatment is a prevalent method used to reduce the ANF in raw soybeans, and the mechanism is called denaturing, by which heat inactivates these ANFs. Extrusion, micronizing, and jetsploding are frequently used in processing. Extrusion is a process in which whole or ground beans are passed forcefully through a barrel using a screw and then exit through a die at the end of the barrel. High temperature, high pressure, and short time are considered basic principles of the extrusion process (Swick, 2020). In extrusion, soybeans are extruded at a temperature of 138 to 150 ^{o}C (Swick, 2020) for 30 seconds to 3 minutes residence time under high pressure (Newkirk, 2010). Extrusion can be wet or dry, combining temperature, time, and moisture variables. If steam preconditioning is used in the extrusion process, it is known as wet extrusion, in which steam is inserted into an extruder barrel. Still, if steam preconditioning is not used, it is called dry extrusion (Mirghelenj *et al*., 2013).

Heat is generated by friction and pressure during the extrusion process. It generally needs a small amount of equipment. Moisture inside the soybeans remains there during the process, so the required amount and duration of heat treatment are reduced (Newkirk, 2010). During extrusion, oil cells are ruptured due to friction, shear, and pressure changes which ultimately results in more digestibility of oil (Nelson *et al*., 1987; Lamsal *et al.*, 2006; Iwanga *et al*., 2007). On the other hand, micronizing is a dry heating method in which radiating heat is used as an energy source. Ceramic plates are used to emit infrared rays but at a higher frequency than a microwave. Gas or electric burners help these ceramic plates at a required temperature. The type of radiation formed during micronizing can enter the absorbent material (Newkirk, 2010). Jet-sploding is another method in which beans are treated to pre-heated air (140 – 315 ^{o}C) rather than directly to flame, causing the heating of grain completely and attaining an inner temperature of 90 – 95 ºC. After heating, beans are mostly shifted into a cylinder mill to conclude the process and ease the release of the intercellular fat (Lázaro *et al*., 2006). Flaking, cooking, and roasting are standard methods used in the processing field and have different effects on the energy level of the product (Waldroup, 1982).

Quality control methods

Unprocessed or under-processed soybeans contain high levels of ANF, which delay growth and development in monogastric animals and young ruminants. Raw FFSB is processed by heat and mechanical means to overcome this problem. Optimal thermal or mechanical processing deactivates ANF found in unprocessed or under-processed soybeans or soybean meals to achieve optimal AA availability. Underprocessing (insufficient heating) will leave the ANF intact, which will result in less availability of AA, and over-processing (excessive heating) will reduce the availability of AA due to the occurrence of the Maillard reaction which occurs between the aldehyde group of sugar and free amino groups (Palić *et al*., 2008).

FFSB as a feed ingredient is associated with SBM but has separate nutritional composition and processing technique than SBM (Willis, 2003; Janocha *et al*., 2022). Several analytical procedures are used to check the quality of processed SBM. Official methods to check the quality of Soybean include the Nitrogen Solubility Index (NSI), Protein Dispersibility Index (PDI), and Urease Activity (UA). At the same time, digestible/reactive Lysine, Protein Solubility in Potassium Hydroxide (KOHPS), and Trypsin Inhibitor Activity (TIA) are commonly used unofficial methods (Palić *et al*., 2008).

Urease Activity as a quality control method for full-fat soybean

UA is a widespread method used worldwide to indicate the quality of processed FFSB due to its simplicity. The AOCS Official Method Ba. 9-58, used for UA determination, is based on the pH change measurement. Experiments were conducted to assess the reliability of this test by analyzing the different samples of FFSB (processed by dry extrusion at five temperatures ranging from 115 to 165 °C) in two different labs and by two different analysts in each lab (Palić *et al.*, 2008) (Table 9).

Palic *et al*. (2008) showed that although the results in one lab were almost similar (performed by two different analysts), the outcome was not very much different. Still, results obtained by different labs had considerable differences, raising the question of this test's reliability. However, the sample processed at a temperature of 135 to 145 °C with urease activity of 0.05 to 0.20 pH change reflected the properties of being adequately processed (Table 10).

Protein Solubility (PS), Protein Dispersibility Index (PDI), and Nitrogen Solubility Index (NSI) as quality control methods

While UA is a widespread test performed to check the quality of SBM, it can only detect the under-processed SBM, not the over-processed. The PS in KOH is a test conducted to check the over-processed SBM. However, very high values are indicative of under-processed meals. Generally, KOH solubility declines as the points of heat treatment surge (Mahesh *et al*., 2017). When combined with other tests, including PDI and NSI, it is beneficial for checking the quality of SBM.

The KOHPS, presented in percentage, is a test carried out by solubility of soybean proteins in a dilute solution of 0.2% KOH (Potassium hydroxide) for 20 mins at room temperature using a magnetic stirrer. Then the sample is centrifuged at 6,000 rpm for 5 mins, and the supernatant is analyzed for protein concentration (Biuret method). The protein content of the KOH extracted solution is divided by the protein content of the original SBM sample (Caprita *et al*., 2010a). The PDI also focuses on the solubility of soybean protein in which the solvent is water. This method uses a blender with the speed of 8,500 rpm, which makes it one of the quickest and most straightforward to perform among all the methods (Palić *et al*., 2011), while NSI is a slow stirring technique. PDI and NSI are two different methods in terms of speed and vigor at which water with soybean product is stirred. In animal nutrition, the PDI method is used as it is a current method and complements KOH solubility and UA to assess the quality of SBM.

Experiments conducted by Karr-Lilienthal *et al*. (2006) in which soybean was extruded at different temperatures followed by expelling revealed that meal produced at the highest temperature of 160 ^{o}C had PS and PDI lower than desirable; however, AA digestibility was most elevated at that temperature. The meal produced at a temperature of 121 and 135 ^{o}C was under-processed due to high urease value and low AA digestibility. Protein solubility was average, but phytate phosphorus was lowest at 160 ^{o}C (Table 11).

Overall, extruded and expelled soybeans have somewhat different quality parameters than SE SBM or FFSB. In the extruded expeller process, oil is collected from extruded soybeans by using mechanical pressure. It is done by a mechanical screw which pushes soybeans through an orifice (Newkirk, 2010). AA digestibility is the best indication of SBM quality (Swick, 2020). Ruiz and Parsons (2015) findings also emphasize that the KOHPS test is not a trustworthy sign of lysine digestibility for FFSB.

Nutrient analysis, apparent metabolizable energy, and ileal amino acid digestibility

Feed costs cover most of any broiler production operation, with feed ingredients contributing to the energy requirement of the broilers. Broilers are raised for meat purposes, and the best results are possible only when the energy requirements of broilers are met along with the other requirements. Generally, broilers' energy requirements are based on metabolizable energy (ME), which is determined simply by subtracting the energy of excreta (urine and feces in chickens) from the gross energy of supplied diet. The feces and urine in chickens are combined as excreta and excreted from the cloaca, a single opening at the end of the digestive tract. Different soybeans may have different values for ME due to different nutrient profiles and processing methods. However, if normal oleic and high oleic soybeans are processed by the same extrusion method, then ME value of both products may remain the same.

Another method to determine energy determination is the usage of the metabolic chamber, which measures the energy loss in the form of heat and gas. This method is costly, labor-intensive, and cannot be applied to many broilers (Kong and Adeola, 2014). Hence, the apparent ME (AME) is commonly used in poultry, and partial excreta collection or total excreta collection methods can be used for it. In the total collection method, total feed energy intake and excreta energy output are determined to evaluate the ME (Sales and Janssens, 2003; Sakomura and Rostagno, 2007). However, this method has drawbacks, including the contamination of excreta with feed, feathers, and intestinal mucosal sloughing, which can affect the results. The partial excreta collection method is applied by adding an indigestible marker, such as titanium dioxide (TiO_2), to the diet, and the ratio of nutrient utilization is checked by using the marker in the diet and excreta (Short *et al*., 1996). Other inert markers include Celite (1%), acid-insoluble ash (AIA), or silica can be used in partial excreta collection. Then, energy utilization % is multiplied by the gross energy of the diet to calculate the AME (Adeola, 2001). This method can consider any miscalculations that may occur with inaccurate measurement of feed intake and excreta output and require various analytical procedures, which may cause an error (Sales and Janssens, 2003). However, the total excreta collection method does not require using an indigestible marker. To date, the ME studies that evaluate both methods' results are limited to poultry (Smeets *et al*., 2015).

For energy determination, chickens are fed an adaptation diet, but there is limited data available regarding the proper adaptation length for feeding experimental diets. In broilers, a basal diet is provided to the chickens for the first 14 days after hatching (Adeola and Ileleji, 2009; Adebiyi *et al*., 2015; Olukosi *et al*., 2017). Experimental diets are then provided to the chickens ranging from 3 to 7 days before sampling. The physicochemical properties of feed can impact the rate at which the nutrients may pass from the intestinal tract, and these properties can even alter the microbial population. So, keeping in view, these things are essential before the collection of samples (Dunaway, 2019).

Generally, the energy values used for poultry feed are taken from the ingredient composition table of the National Research Council 1994. Still, this data was obtained from adult cockerels and may not be suitable, especially for young chickens. The digestive capacity of chickens increases with age, especially for the SBM (Krás *et al*., 2013) and the development of accessory organs and the digestive system itself (Thomas and Ravindran, 2008). Modern broilers show better energy efficiency than commercial broilers from the past. The broiler feed conversion ratio (FCR) is altered mainly by energy diet content (Willems *et al*., 2013). Also, the dietary energy description impacts the technical and economic broiler operation (Basurco *et al*., 2015). Using a reference diet based on corn or SBM can result in ME values that are near the actual nutritional requirements of broiler chickens; however, inadequate digestion and absorption of the fat are clearly established in young chickens (Saki *et al*., 2011). The difference between energy values with and without correction of retained N shows the significance of considering the N substances which will be retained or excreted as uric acid (Liu *et al*., 2017). The ME values are fixed for N retention for the objective of comparison with the idea that all retained N will be expelled from the body as uric acid when all data will be on N equilibrium (Lopez and Leeson, 2008). For the broilers, increased body N retention happens significantly during the initial and growing phases, and the correction will be more considerable for mature broilers (Bertechini *et al*., 2019).

Marker is a term used for a material that is used for qualitatively and quantitatively estimating the nutritional phenomenon and examining the digestive process both physically and chemically. A good marker has some qualities, such as a known, non-toxic substance that remains unchanged during the gastrointestinal tract passage, is easy to analyze, completely recovered in excreta, and must not affect the physiological process of the digestive tract (Kotb and Luckey, 1972). But no such marker meets all these requirements (Marais, 2000). Marker recovery rate is a crucial criterion when markers are used to study the digestibility of feedstuff, although few studies are available only to report this rate (Sales and Janssens, 2003). Some factors can influence the marker recovery rate, for example, the amount of marker included in the diets. Diet composition can also be believed to impact nutrient estimates when markers are used, as some contents (fiber) may influence the feed passage rate and, therefore, marker recovery rate (Dourado *et al*., 2010).

Nutrient digestibility can be affected by other factors, such as the age of the chicken. The digestive system of the young chicks is immature and has less ability for nutrient absorption as compared to the older chickens. The intestinal tract of the broilers has not completed the ability to digest the dietary nutrients until the age of two weeks (Vieira and Moran, 1999). It could be because broilers may have less endogenous enzyme production (Olukosi *et al*., 2017). As the broiler grows during the early stages, the ability to absorb carbohydrates and fats is reduced compared to other phases of life. Young chicks have a lower percentage of absorption for lipid (82%), carbohydrates (82%) and protein (78%) when compared to older chickens (Noy and Sklan, 1995). Also, the inclusion level of test ingredients can affect the estimated ME in the test diet. So, this factor should also be considered and managed with consideration of commercial practice. Because using the high inclusion level of test ingredients will cause a nutritional imbalance in the test diet, while lowering it will lead to more variability between determined ME values (Leeson *et al*., 1977; Mateos and Sell, 1980).

Extruded-expeller soybean (EESB) is an alternative to the SE SBM (Janocha *et al.*, 2022) and is mainly used in organic poultry feed (Powell *et al.*, 2011). Due to its high oil content of 5 to 8 %, it has elevated AMEn of ~2,751 kcal/kg (Newkirk, 2010) and it is an excellent second option for ME and digestible AA in broilers' diets. However, published ME values of EESB for broilers are limited (Powell *et al*., 2011). Lopez and Lesson (2008) calculated the AME corrected by nitrogen (AMEn) values of SBM as 1,986, 2,286, and 2,477 kcal/kg when SBM was added at a rate of 10, 20, and 30%, respectively, in a complete corn-SBM based diet to the broilers of 30 to 33 days age. Powell *et al*. (2011) reported the MEn value of EE-SBM as 2,882 kcal/kg DM for broilers, but there is limited data available for AMEn for EESB and FFSB in broilers, and more research is needed.

In broilers, determining digestibility at the terminal part of the ileum is considered a better measure of AA absorption (Ravindran *et al*., 2017). It is better to describe the available AA in terms of digestible AA than total AA as digestible AA becomes accessible for maintenance and production purposes (Lemme *et al*., 2004). For feed ingredients, the standardized ileal digestibility (SID) of AA is used to calculate the digestibility of AA for broilers (Kong and Adeola, 2014). But SID of AA may be affected by the specific factors of feed ingredients (Park *et al*., 2020). Kong and Adeola (2013) described providing nitrogen-free diets (NFD) containing dextrose without corn starch to broilers had more basal endogenous losses (BEL) of CP and most AA as compared to those who fed NFD containing dextrose and cornstarch or corn starch without dextrose. So, the carbohydrates source in NFD may affect the BEL of CP and AA in broiler chickens. If diets contain less digestible ingredients, then broilers will respond to them, and due to this well-recognized fact, diets are now formulated based on the digestible AA (Ravindran and Bryden, 1999). Excreta of broilers consists of feces and urine, and urinary nitrogen is a source of error while determining CP digestibility. In the hindgut, ileal undigested AA can be fermented, while gut flora may also synthesize them. But AA that is synthesized in the hindgut is not used by the host chicken. So, the fecal digestibility of AA overestimates the digestibility of AA. As this concept of AA values has been accepted as a valuable tool in poultry feed formulation, it is also acknowledged that analysis of ileal digesta should be considered for AA digestibility determination (Ravindran *et al*., 1999). So, it is crucial to consider all the procedure and essential steps for digestibility assay, which includes formulation and mixing of diets(s), *ad libitum* feeding of broilers for a predetermined period, euthanasia, collection of ileal digesta, processing of digesta and analysis of ingredients, diets, and digesta. Any of these steps can influence the determination of AA digestibility (Ravindran *et al*., 2017).

As the feed passes through the digestive tract, it can cause endogenous losses. Endogenous N or CP and AA are defined as the amount of these constituents in ileal digesta or feces, which do not originate from the diet (Souffrant, 1991). The endogenous protein consists of salivary and gastric secretions, pancreatic and bile secretions, small intestinal secretions, mucoproteins, and sloughed epithelial secretions (Jansman *et al*., 2002). The bacterial protein that can originate from either dietary protein or endogenous proteins due to microbiota activity in the small intestine is usually included in the estimation of the endogenous protein (Moughan *et al*., 2005; Miner-Williams *et al*., 2009). Basal endogenous losses are essential to consider during AA digestibility studies in chickens. These losses are used to calculate the AA SID values for feed for broilers and expressed in mg per kg dry matter (DM) intake. Likewise, the AA digestibility, these endogenous loss values can be affected by the quantification method, age of the animal, and phytate or phytase presence in the diet.

Ravindran *et al*. (2014) researched four samples of FFSB taken from commercial feed mills in Southeast Asia to check the nutrient analysis, AME, and ileal AA digestibility using lab analysis and studies on broilers. As per their findings, FFSB holds more dietary fat and AME than SE SBM but less digestible content of protein and AA. However, in SE SBM, dietary fat content is reduced, which increases the protein content of meals on a DM basis compared to FFSB. In the four samples, CP, fat, AME, and standardized ileal digestibility coefficient of protein ranged from 351 to 399 g/kg, 177 to 192 g/kg, 12.62 to 15.46 MJ/kg, and 0.763 to 0.821, respectively. This work, however, has two limitations; first, only four samples were taken for evaluation, and second, these samples were collected from commercial feed mills with unknown processing history.

Enhancing the nutritional value of soybeans using enzymes

The addition of enzymes in poultry diets can improve production efficiency, which is achieved by increasing the digestion of low-quality products and minimizing nutrient loss via excreta. There are various benefits that exogenous enzymes can have in diets, including increasing digestibility, eliminating ANF, enhancing nutrient availability, and environmental well-being (Costa *et al*., 2008). In the feed, complex nutrients and enzymes catalyze those during digestion. These facts are critical about proteases because the proper absorption of nitrogenous compounds in feedstuff is necessary for less nitrogen excretion, which is a significant pollutant worldwide (Dosković *et al*., 2013). Therefore, microbial proteases are protein digestive enzymes used in poultry diets to break down protein and proteinaceous anti-nutrients in different plant materials. The chickens have endogenous enzymes, but nutrients are still not fully digested and absorbed due to the chicken's natural inefficacies. In chickens, most microbes are present in the ceca, but little absorption happens there, so supplementing broilers feed with exogenous enzymes becomes important (Ravindran, 2013). The main exogenous enzyme classes used in poultry are carbohydrases, phytases, and proteases, and they catalyze the carbohydrates, phytases, and proteins in small and simple forms for better absorption.

Feed ingredients of plant protein sources such as SBM may have high levels of non-starch polysaccharides (NSP) and antinutritive effects, enhancing digesta viscosity and reducing the broiler's performance. These NSPs may originate from cereal grains and plant protein sources and contribute to one of the significant factors affecting carbohydrate utilization in broilers (Wagner and Thomas, 1978; Antoniou *et al*., 1981; Bedford *et al*., 1991; Slominski, 2011). The main NSPs present in the SBM are arabinans, arabinogalactans, galactans, galactomannans, mannans, and pectic-polysaccharides (Slominski, 2011). Carbohydrase may be added to feed to mitigate these adverse effects. However, the suitable enzyme and its inclusion dosage in the feed may differ depending on the ingredient (Dunaway, 2019). For various ingredients, carbohydrase is helpful when added to diets, but on combining, an additive effect may or may not be seen (Cowieson *et al*., 2006). Oligosaccharides in soybeans are sugar-based compounds that chickens cannot digest. The main compounds in this category are raffinose and stachyose (Newkirk, 2010). Reducing the oligosaccharides content by alcohol extraction can increase the ME of SBM by 7 to 10% (Parsons *et al*., 2000).

Erdaw *et al*. (2017) studied broilers' growth and physiological response when fed diets containing raw FFSB supplemented with high-impact microbial protease. Raw FFSB was added at 0, 10, and 20% to replace SBM, and three levels of mono-component protease, derived from *Nocardiopsis prasina* were added at 0.1, 0.2, and 0.3 g/kg diet (equivalent to ~7,500, 15,000, and ~22,500 protease units/kg diet, respectively) for 0 – 35 days. By increasing the raw FFSB in diets, there was an increase in weight of the pancreas by 24, 32, and 26% at days 10, 24, and 35, respectively, but a decrease in apparent ileal digestibility (AID) of CP and AA at day 24. Pancreatic protein content was decreased, but with protease supplementation, it was increased. The highest villus length and mucosal depth were observed and compared to others (day 24) when 20% raw soybean meal (RSBM) was given with 0.2 gm protease/kg. It is important to note that raw FFSB and protease supplementation did not significantly affect the body weight of broilers in the entire period (0 – 35 days). There is room for an increased inclusion level of raw FFSB in broiler diets, as productivity was not significantly compromised by the partial replacement of commercial SBM with raw FFSB.

Besides TI, soybean also contains phytate and NSP, two other ANF. Phytase can interfere with the absorption of minerals in chickens and thus affect their performance. As these are not heat-labile, supplementing the chicken's diet with exogenous enzymes is recommended. Phytase combined with protease has good synergistic effects and can benefit broilers' health. Also, enzymes can help increase the energy value and N retention of diet and gain bodyweight of broilers (Erdaw *et al*., 2016). As mentioned in Table 14, supplementing the wheat-based diet with protease and carbohydrase increased the AME value by 234 kcal/kg and N retention by 4.8%. Supplementing the corn/SBM diet with phytase and multi-carbohydrase increased the BWG by 41.5 g, the AME value by 74 kcal/kg, and N retention by 1.8 %.

Uses of high oleic full-fat soybeans in broiler diets

FFSB is a worthy feed ingredient in broiler diets due to its higher fat and AME than SE SBM. Because of its high-fat content, adding fat to the poultry diet is a considerable choice. However, the economic viability and inclusion rate should be checked before practicing it (Ravindran *et al*., 2014). High oleic soybean oil can potentially be used as an oil source for poultry feed and human food production (Peckman, 2020). In a study conducted by Rodriguez *et al*. (2005), it was observed that dietary inclusion of high oleic acid sunflower seed (HOASS) had an effect ($P < 0.001$) on body weight and the feed-to-gain ratio of broilers at 42 d. Broilers fed 100, and 200 g of HOASS/kg diet had low weight and a poorer feed-to-gain ratio than those fed on a diet containing no HOASS. In another study conducted by Viveros *et al*. (2009), the performance of broilers was not affected by fat source or high oleic acid sunflower hulls supplementation at 21 d. Also, the digestive organ size (relative liver and pancreas weight and relative duodenum, jejunum, ileum, and ceca lengths) was not affected.

An experiment conducted by Mirghelenj *et al*. (2013) revealed that wet extruded FFSB could be used up to 15% in broiler diets. In their experiment, FFSB was wet extruded at a temperature of 155 ^{o}C for 15 sec and added in four feed samples at 0, 7.5, 15, and 22.5 % in place of dehulled SBM and soybean oil. The growth performance of the broiler was not influenced when extruded FFSB was added up to 15%. However, when 22.5% extruded FFSB was added, there was less feed intake due to more fat in the diet and weight gain. At the same time, there was also a reduction in mucosa absorptive surface in the duodenum and jejunum of broilers. The pancreas's weight was slightly higher than the control at 21 days, but it was normal at 42 days (Table 15).

This study follows other studies conducted by different researchers. Researchers introduced the heat-treated FFSB up to 15% in broiler diets and concluded that body weight at 6 weeks was not affected badly (Papadopoulos and Vandoros, 1988). While growth performance of broilers fed with 15% FFSB was equal to or better than those provided with a diet containing 15% SBM and soybean oil (Wang *et al*., 2000). According to a study, the inclusion rate of extruded FFSB up to 20% has no adverse effects on broiler performance (Todorov *et al*., 1999). It was also presented that chickens' performance was not affected at 21 and 42 days when EFFSB was added into the diet up to 14% (Subuh *et al*., 2002). Another study mentioned that the FCR of the broiler at the age of 1 to 21 days was not affected when feed containing FFSB extruded at a temperature of 138 to 154^{o}C was added at any substitution level with SBM (Zhang *et al*., 1993).

A study by El Sherif, 1996 found that when extruded soybeans were added to broilers' diets in replacement of SBM at 10 and 20%, the final body weight and feed conversion index were better in broilers than those fed on SBM and 10% extruded soybeans replacement (Table 16). In a study conducted by Peckman (2020), there was a decrease ($P < 0.05$) in body weight and feed intake of broilers at 42 d fed on high oleic soybean meal (HO SBM) and oil than broilers fed on traditional SBM and oil (2.72 vs. 2.90 kg and 2451.67 vs. 2647.61 g, respectively). However, no significant effect was observed on FCR in this study. Reduction in feed intake can result in a slightly more significant fat percentage in HO SBM and oil than in traditional SBM and oil. An increase in energy level within a diet can start a reduction in feed intake (Gatlin *et al*., 2002).

Fatty acid profile in soybeans

Fatty acids are carboxylic acids having hydrocarbon chains varying from 4 to 36 carbons (Uhegbu *et al*., 2013). When present in natural fats, generally, they are straight-chain derivatives with an even number of carbons (Harwood, 1988). They are the building blocks of lipids, which are considered a concentrated energy source in broiler feed. Lipids provide the essential fatty acids that help absorb fat-soluble vitamins. In the small intestine of chickens, digestion and absorption of lipids occur mainly (Uni *et al*., 1995). Oleic acid is an important fatty acid, and metabolic studies have shown similar efficacy in reducing low-density lipoprotein (LDL) cholesterol compared to linoleic acid (Wood and Enser, 2017). Due to the high usage of broiler meat in the human diet, it has good potential to positively impact human health by creating functional food (Mir *et al*., 2017). In a study by Azcona *et al*. (2008) on conducted Argentinean "Camperos" male chickens, the chickens fed on ground linseed and high oleic sunflower seeds had a better ratio of omega-9 monounsaturated fatty acids (MUFA) and omega-3 polyunsaturated fatty acids (PUFA) in breast and leg meat than chickens fed on traditional corn/soybean diet.

Lipid sources in poultry diets usually come from fats and oils such as poultry fat, soybean, or corn oil. Sources like EESB or FFSB may become important ingredients with good lipids content. Although there is data available showing that providing soybean oil is also more digestible in comparison with intact soybean oil from SBM, which is encapsulated in the seed (Kim *et al*., 2013; Tancharoenrat *et al*., 2014; Su *et al*., 2015) but EESM or FFSB has more oil content then SE SBM which may have a more economic advantage. The monogastric's fatty acid profile reveals the diet's fatty acid profile (Mir et al., 2017), so the content of fatty acids in soybean diets can also affect the final fatty acid composition of the broiler carcass. Studies conducted by Hsieh *et al*.

(2002), Azcona *et al*. (2008), and Toomer *et al*. (2020) all demonstrated that the significant increase in the concentration of MUFA of breast and thigh muscles analyzed from broilers fed on diets high in MUFA. It can also be beneficial for marketing value-added chicken products with more content of healthy fatty acids profile.

Conclusion

Genetic modifications in soybeans, which resulted in high oleic soybeans, are a valuable ingredient that can be used in broiler diets. Its rich profile in oleic acid can be a valuable tool to manipulate the fatty acid composition of the meat products of chickens, which can ultimately positively affect human health, especially cardiovascular health. It can be processed by extrusion, which can result in FFSB. FFSB is used in poultry ration as a protein and energy source in place of SE SBM or EESB. FFSB use is rising on a commercial scale as it offers a blend of protein and oil with less variability in composition. But it can be achieved only if it is adequately processed, destroying ANF and simultaneously keeping the AA intact. However, economic factors should be considered while making such decisions.

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Table 1. Comparative amino acids composition of soybean meals.*

Nutrient	Soybean	
	Solvent extracted SBM (48% CP)	**Full-fat soybean**
Dry Matter, (%)	90.00	90.00
Crude protein, (%)	48.00	38.00
Dig. energy, (kcal / Kg)	3,559	4,657
Crude fiber, (%)	4.20	5.50
Dig. Lysine, (%)	2.63	2.11
Dig. Threonine, (%)	1.58	1.30
Dig. Methionine, (%)	0.60	0.52
Dig. Isoleucine, (%)	0.61	1.58
Dig. Tryptophan, (%)	0.59	0.43
Fat, (%)	2.50	19.00
Available Phosphorus, (%)	0.24	0.19
Calcium, (%)	0.30	0.23

*(Willis, 2003)

Table 2. Nutrient content of whole soybeans and different soybean meals (SBM).*

Nutrient	Soybean			
	Full-fat soybean, cooked	**Expeller soybean**	**Solvent extracted SBM**	**Dehulled, solvent SBM**
Dry Matter, (%)	90.00	89.00	90.00	88.00
Energy, (kcal/kg)	3,350	2,420	2,240	2,425
Crude protein, (%)	38.00	42.00	44.00	47.80
Ether extract, (%)	18.00	3.50	0.50	1.00
Crude fiber, (%)	5.00	6.50	7.00	3.00
Calcium, (%)	0.25	0.20	0.25	0.31
Methionine, (%)	0.54	0.60	0.65	0.70
Lysine, (%)	2.40	2.70	2.70	3.02

*Batal and Dale (2016) Feedstuffs ingredient analysis table. The University of Georgia, Athens, GA.

Table 3. Amino Acid balance in full-fat soybean protein compared with the “ideal balance” required by poultry. Figures relative to Lysine (100).*

Amino Acid	Full-fat soybean Protein	“Ideal” Protein (Starter)
Lysine	100	100
Methionine + Cystine	49	76
Threonine	61	63
Tryptophan	20	17
Leucine	120	126
Isoleucine	75	72
Valine	75	79
Histidine	40	40
Phenylalanine + Tyrosine	136	121
Arginine	121	108

*Wiseman, 1994

Table 4. Apparent digestibility (%) of amino acids in soybean meal (SBM) products fed to poultry.*

Amino Acids	Solvent extracted SBM		Extruded /Expeller meal (43% CP)	Full fat soybean	
	44% CP	De-hulled (48% CP)		Extruded	Roasted
Methionine	91.00	91.00	91.00	86.00	82.00
Cysteine	86.00	86.00	82.00	77.00	76.00
Met + Cys	88.00	88.00	86.00	81.00	79.00
Lysine	91.00	91.00	93.00	88.00	81.00
Threonine	89.00	89.00	89.00	85.00	79.00
Isoleucine	92.00	92.00	92.00	87.00	79.00
Histidine	93.00	93.00	92.00	87.00	86.00
Valine	91.00	91.00	90.00	86.00	77.00
Leucine	92.00	92.00	94.00	87.00	80.00
Arginine	92.00	92.00	97.00	91.00	85.00
Phenylalanine	93.00	93.00	94.00	88.00	80.00

* Newkirk, 2010

Table 5. Fatty acid profile of soybean oil and soybean seed.*

Major Fatty Acid	(g/kg Oil)[1]	Range (%)[2]	(%)[2]	(%)[3]	(%)[4]	High oleic-Plenish variety (%)[5]	Soybean seeds % of Dry Matter[4]
C 16:0 (palmitic)	105	7.00 - 12.00	10.70	10.00	7.00-12.00	6.00	1.44 – 2.31
C 18:0 (Stearic)	40	2.00- 5.50	3.90	4.00	2.00-5.00	4.00	0.54 – 0.91
C 18:1 (Oleic)	250	20.00 - 50.00	22.80	18.00	19.00-34.00	76.00	3.15 – 8.82
C 18:2 (Linoleic)	520	35.00 - 60.00	50.80	55.00	48.00-60.00	7.00	6.48 – 11.60
C 18:3 (Linolenic)	70	2.00 - 13.00	6.80	13.00	2.00-10.00	2.00	0.72 – 2.16

* [1] Wiseman, 1994; [2] Perkins, 1995; [3] Clemente *et at*., 2009; [4] El-Shemy, 2011; [5] Knowlton, 2022

Table 6. Content of vitamins in seeds and soybean products.*

Vitamins	Soybean meal		Soybean		
	Solvent[1]	Dehulled solvent[1]	Expeller[1]	Full-fat[1]	Whole and roasted
E, (mg/kg)	3.0	3.3	6.6	31	31
Thiamine, (mg/kg)	1.7	1.7	1.7	6.6	6.6
Riboflavin, (mg/kg)	3.0	2.6	4.4	2.64	2.64
Pantothenic acid, (mg/kg)	13.3	13.2	13.8	15.6	15.6
Biotin, (µg/kg)	320	320	320	286	286
Folic acid, (µg/kg)	450	700	450	3542	450
Choline, (mg/kg)[2]	2743[2]	2850[2]	2673[2]	N/A[1]	2420[2]
Niacin, (mg/kg)	59.8	20.9	36.7	22.0	22.0

*[1] El-Shemy, 2011; [2] Newkirk, 2010

Table 7: Content of minerals in seed and soybean products.*

Mineral Components	Soybean seeds (g/kg)[1]	Solvent extracted SBM 44% CP (g/kg)[1]	Whole soybean roasted (%)[2]	Solvent extracted SBM[1] (%)[2]
Calcium	2.62	3.12	0.25	0.25
Phosphorus	5.70	6.37	0.59	0.60
Magnesium	2.80	2.72	0.21	0.27
Potassium	15.93	19.85	1.70	1.97
Sodium	0.29	0.18	0.04	0.04

*[1] El-Shemy, 2011; [2] Newkirk, 2010

Table 8. Apparent metabolizable energy (AME), Nitrogen retention (NR), and Cresol red absorption of processed full-fat soybean (FFSB).

Process of FFSM	AME (Kcal / kg)[1]	NR (%)[1]	Cresol red absorption (%)[2]
Wet Extrusion	4,278	54.00	4.60
Dry Extrusion	4,159	59.00	4.06
Micronized	3,681	48.00	4.00
Jet – Sploded	3,513	61.00	3.98
Toasted	3,728	57.00	3.81
Raw	3,227	30.00	2.50

[1]Wiseman, 1994; [2]Lázaro *et al.*, 2006

Table 9. Urease activity (UA) in full-fat soybean processed at different temperatures obtained by two laboratories and their effect on average body weight gain (BWG) and feed conversion ratio (FCR) of chickens from 0 – 14 days of age.*

Heat (°C)	BWG (g)	FCR	UA (Δ pH)	
			Lab[1]	Lab[2]
115	92.2	1.953	2.189	1.876
125	105.1	1.735	0.433	0.239
135	135.5	1.35	0.080	0.069
145	138.6	1.335	0.026	0.044
165	85.3	1.899	0.028	0.035

*Palić *et al.*, 2008

Table 10. Relation between the temperature of extrusion, degree of full-fat soybean (FFSB) processing, and urease activity (UA).*

Temperature of extrusion (°C)	Degree in FFSB processing	UA (Δ pH)
< 135	Under – processed	> 0.20
135 – 145	Adequately processed	0.05 – 0.20
> 145	Over – processed	< 0.05

*Palić et al., 2008

Table 11. Chemical composition, protein quality indices, and amino acids digestibility of soybean meals produced at various temperatures during extruder/expeller processing (% dry matter basis).*

Item	Processing temperature			
	121 °C	135 °C	150 °C	160 °C
Dry matter, %	93.80	94.63	95.40	95.90
Crude protein, %	48.53	48.61	49.48	49.77
Total phosphorus, %	0.69	0.68	0.69	0.69
Phytate Phosphorus, %	0.54	0.54	0.55	0.42
Non-Phytate Phosphorus, %	0.15	0.14	0.14	0.27
PDI, %	55.66	43.53	20.49	10.09
KOH Protein Solubility, %	82.57	78.03	72.94	61.64
Urease activity, pH units	2.11	1.91	0.06	0.02
Lysine, %	75.00	73.50	87.10	89.30
Methionine, %	72.30	66.10	87.10	90.10

* Karr-Lilienthal, 2006

Table 12. The nutritional composition and some quality parameters of full-fat, raw whole soybeans, and conventional soybean meals (SBM).*

Types of SBM	**Crude protein (%)**	**Ether extract (%)**	**Starch† (Sucrose††)**	**Crude fibre (%)**	**Urease activity ΔpH**	**KOH protein solubility (%)**	**Metabolizable energy (kcal/kg)**	**References**
Conventional SBM	44 - 50	3-Feb	-	3	-	-	-	Heuzé *et al.*, 2015
	46.3 - 48.1	0.9 - 2.9	-	3.9 - 5.2	0.0 - 0.01	68.1 - 84.0	3,524	Serrano *et al.*, 2012
	46.4 - 48.2	1.09 - 2.05	††5.42 -8.29	3.63 - 6.08	0.007 - 0.081	69.7 - 74.3	2,000 - 2,375	Ravindran *et al.*, 2014 A
Full-fat SBM	36 - 42	18 - 22	-	-	-	-	-	Stein *et al.*, 2008
	38	20.9	-	5.1	0.28	-	-	Senkoylu *et al.*, 2005
	35.1 - 39.9	17.7 - 19.2			0.30 - 0.02	81.1 - 63.1	3,016 - 3695	Ravindran *et al.*, 2014
Raw full-fat SBM	37.08	18.38	-	-	-	-	-	Van Eys *et al.*, 2004
	36.5 - 43.2	20.7 - 22.2		2.5 - 8.3	-	-	-	Sharma *et al.*, 2013
	39.4 - 44.4	14.0 - 18.7	†4.3 - 6.7	-	1.99	-	-	Sharma *et al.*, 2014

* Erdaw *et al.*, 2016

Table 13. Main effects of raw soybean meal and protease supplementation on live body weight (g/broiler) and weight of pancreas (g/100 g body weight).*

Items	Live body weight (g)			Weight of Pancreas (g/100g BW)		
	10 d	24 d	35 d	10 d	24 d	35 d
RSBM (%)						
0	282	1,463	2,540	0.54	0.23	0.15
10	279	1,420	2,432	0.61	0.31	0.2
20	265	1,419	2,464	0.71	0.34	0.21
Protease (g/kg)						
0.1	270	1,424	2,422	0.62	0.29	0.19
0.2	275	1,415	2,461	0.61	0.29	0.19
0.3	282	1,463	2,549	0.64	0.29	0.18
Sources of Variation						
RSBM	0.001^a	0.123^b	0.10^c	0.001^a	0.001^a	0.01^b
Protease	0.005^b	0.03^d	0.06^e	0.102	0.612	0.423
RSBM x Protease	0.511	0.432	0.712	0.231	0.641	0.451

Abbreviations: RSBM, raw soybean meal; BW, body weight

a $P < 0.001$, b $P< 0.01$, c $P > 0.05$, d $P < 0.05$, e $P = 0.06$ *Erdaw *et al*., (2017)

Table 14. The additional response over the control diets of broilers fed diets supplemented with enzyme combination (cocktail).*

	Combined with	Base of diet	Type of chickens	Body weight gain	Apparent metabolizable energy (kcal/kg)	Retained Nitrogen %
Protease	Carbohydrase	Wheat	Broiler	-	234.2	4.8
	Phytase	Corn/SBM	Broiler	14%	100	-
	Phytase	Corn/SBM	Broiler	-	103	0.15
	Xylanase + Amylase	Corn/SBM	Broiler	-	64.53	0.6
Phytase	Multi-carbohydrase	Corn/SBM	Broiler	41.5 g	74	1.8
	Xylanase	Wheat	Broiler	15.40%	0.67	2.1

*Erdaw *et al*., 2016

Table 15. Effect of dietary inclusion rate of extruded full-fat Soybean (EFFSB) on feed intake, weight gain, and feed conversion ratio (FCR) of broiler chickens.*

Item	**Feed intake (g/broiler/d)**	**Weight gain (g/broiler/d)**	**FCR (g:g)**
	Age (d)	Age (d)	Age (d)
Dietary level of EFFSB (%)	0 – 42	0 – 42	0 - 42
0	86.83	46.7	1.86
7.5	84.2	44.2	1.9
15	83.88	45.2	1.84
22.5	81.59	43.3	1.88

* Mirghelenj *et al*., 2013

Table 16. Use of dry extruded soybeans in chickens.*

	Soybean meal	**Level of beans (%)**	
		10	**20**
At 21 days			
Live weight, (g)	625	570	585
Feed consumed, (g)	1,083	1,024	989
Conversion index, (g/g)	1.73	1.79	1.69
At 45 days			
Live weight, (g)	1,975	2,050	2,120
Feed consumed, (g)	4,572	4,460	4,436
Conversion index, (g/g)	2.31	2.117	2.09

* El Sherif, 1996; Lázaro *et al*., 2006

CHAPTER 2

Effects of high oleic full-fat soybean on live performance, carcass and meat quality, and meat fatty acid composition of broilers

Abstract

High oleic soybean may positively affect broiler meat quality. This experiment evaluated the effects of normal oleic extruded expeller (NO-EE), normal oleic full-fat (NO-FF), and high oleic full-fat (HO-FF) soybean on broiler live performance, carcass and cut-up parts yield, and meat fatty acid composition. These extruded soybeans (SB) were produced in the same location under similar processing conditions. SB's nutrient and energy content were obtained by near-infrared spectroscopy (NIRS) and wet chemistry. Diets were formulated to be isoenergetic, isonitrogenous, and had identical digestible Lys, TSAA, Thr, Val, Ca, and available P in the three feeding phases. Five hundred and forty Ross-708 male broilers were raised on floor pens, with 18 broilers per pen and ten replicates per treatment in a completely randomized design. Chickens were fed starter diets in crumbles up to 14 d of age, while grower (15 – 35 d) and finisher diets (36 – 47 d) were fed in pellets. Chickens were weighed at 7, 14, 35, and 47 d. At d 48, four broilers per pen were processed and cut up in parts. Breast samples were collected and evaluated for quality and fatty acid content. Broilers fed diets with NO-EE were heavier ($P < 0.05$) than chickens fed diets with full-fat soybeans (FFSB) at d 7 (176 g), 14 (526 g), and 35 d (2,494 g), but no treatment effect ($P > 0.05$) was observed at 47 d of age. Feed conversion ratio (FCR) of NO-EE was better ($P < 0.05$) than HO-FF at 7 d and 47 d, while NO-FF had intermediate results. At d 35, broilers fed NO-FF had similar FCR than NO-EE and better than those fed HO-FF SB. Carcass yield was also higher for broilers fed NO-EE than HO-FF, while NO-FF was intermediate. No effects of dietary treatments were detected ($P > 0.05$) on cut-up part yields. After 24h, breast pH was lower for HO-

FF than NO-EE and NO-FF. Treatments did not affect breast meat color, cooking, and dripping loss ($P > 0.05$). Breast fillets without wooden breast (score 1) were higher ($P < 0.05$) for NO-FF than the other two treatments. There were no significant effects ($P > 0.05$) of SB source on white stripping or spaghetti muscle. The breast meat fatty acid profile (g fatty acid/ 100 g of all fatty acids) was affected ($P < 0.001$) by the SB source. Broilers fed diets containing HO-FF SB had 54 to 86% more oleic acid in the breast muscles than NO-FF and NO-EE. In contrast, the linoleic acid was reduced by 42 to 57% in broilers fed HO-FF. Saturated fatty acids like palmitic and stearic had the lowest concentration in meat from HO-FF broilers. In conclusion, broilers fed HO-FF enriched oleic acid content of breast meat while reducing the saturated fatty acid content but had lower live performance and carcass yield than NO-EE SB. HO-FF SB may enhance the quality of broiler meat.

Keywords: Breast meat, broilers, fatty acids, performance, soybean meal.

Introduction

Soybean (*Glycine max*) is one of the broilers' most common dietary components. It is widely used due to its high nutritive value, which includes high protein, digestible amino acids (AA), and high energy content (Waldroup, 1982; Perez-Maldonado *et al*., 2003; Rocha *et al*., 2014). It is cost-effective in supplying essential AA, especially lysine (Lys), methionine (Met), and threonine (Thr), while it is lower in crude fiber (CF) than most other oilseed meals. Traditionally, the extracted oil seed cake is mainly used as a high-protein meal in broiler diets. Generally, full-fat soybeans (FFSB) are a good source of protein and energy and can replace the solvent-extracted soybean meal (SE SBM) in poultry diets. However, in a typical corn-soybean meal diet, corn is considered a major energy source (Odjo *et al*., 2015; Córdova-Noboa *et al*., 2021). Raw soybeans (SB) contain several anti-nutritional factors (ANF) (Foltyn *et al*., 2013). Two main soy ANF affecting broiler performance are trypsin inhibitors (TI) and lectins (Newkirk, 2010). Others include anti-vitamins, saponins, tannins, non-starch polysaccharides (NSP), and phytate (Dourado *et al*., 2011). Extruded expeller soybean (EE-SB) and FFSB are also valuable for organic poultry farming. Still, the ability of chicken to fully utilize the nutrient content of soybeans depends on the processing method to produce the meal (Powell *et al*., 2011).

FFSB, due to its high oil content, is a good energy source and can save oil extraction costs, but there may be ANF in FFSB that can limit its use in chicken’s diet. The most common methods to eradicate ANF in soybeans are heat treatment and extrusion processing. Extrusion processing may utilize wet or dry techniques (Mirghelenj *et al*., 2013) at high temperatures and pressure but for a short time (Björck and Asp, 1983). In this study, the dry extrusion method was used. However, steam pre-conditioning may increase the efficacy of extrusion (Babar *et al*., 1988; Bressani and Sosa, 1990; Carlini and Udedibie, 1997). Milczarek *et al*. (2017) concluded that extrusion of raw SB had a beneficial result on the nutritional values of beans and extruded SB can be used as a partial substitution for protein (30% in starter and 50% in grower and finisher diets) from SE SBM in broiler diets. Still, raw SB should be avoided in these quantities due to adverse effects on growth and performance. Wiriyaumpaiwong *et al*. (2004) compared the effect of heat processing of SB by extrusion with air heating whole beans. They concluded that the extruded SB product was more consistently heat-treated, although more expensive.

Oil can be recovered from SB by applying mechanical pressure in expeller extraction processing. This is accomplished using a mechanical screw that forces SB (typically cracked to facilitate the process) through an orifice (Newkirk, 2010). Small openings in the expeller unit's barrel allow the oil to come out while the seed stays inside the barrel. The utilization of FFSB has gained more popularity in the SB-growing regions, which lack oilseed processing plants. Hence, the shipping cost of sending the SB to a large solvent-extracted plant and shipping meals back can be avoided. Extrusion setup can be managed in these conditions, which will be more practical and economically attractive. Some regions have significantly less supply of SE SBM because there are no large solvent extraction plants. In those regions, an extruded expeller soybean may be an alternative source to SE SBM or FFSB. The expelling process does not typically produce heat, so additional heat is necessary to destroy TI, the most crucial proteinaceous ANF that can affect the intake, digestion, absorption, and metabolism of nutrients and the animal's performance. (Liener and Kakade, 1980; Nitsan and Nir, 1977). TI can be destroyed by heat, so trypsin inhibitor activity (TIA) may be changed within different soybean sources depending upon which processing method was used (Clarke and Wiseman, 2005).

Meat quality can be affected by many variables that are complex and present throughout the production chain (Baracho *et al*., 2006; Petracci *et al*., 2010). The pH, water holding capacity, drip, cooking losses, and myopathies are a few of them essential for manufacturing processors of value-added meat products. These variables are necessary to control, guaranteeing a final product of exceptional quality and profitability (Allen *et al*., 1998). The appearance, texture, juiciness, firmness, tenderness, odor, and flavor are considered the most critical and perceptible meat features that influence the initial and final meat quality characteristics before and after a meat product purchase (Cross *et al*., 1986).

The dietary fatty acid profile is reflected in meat tissue fatty acid content, and chickens' nutrition significantly impacts their meat quality and safety (Mir *et al*., 2017). For example, monounsaturated fatty acids (MUFA) are present in seeds of high oleic acid sunflower varieties, and their addition to diets of monogastric species is beneficial to the fatty acid profile of abdominal fat and blood serum (Viveros *et al*., 2009). It can improve the degree of unsaturation of intramuscular fat without any adverse effect on lipid oxidation that is linked with dietary polyunsaturated fatty acids (Rodríguez *et al*., 2005). There is growing evidence that cardiovascular health can be positively affected by diets enriched with MUFA. These diets can lower low-density lipoprotein cholesterol without lowering high-density lipoprotein cholesterol in blood plasma (Lichtenstein *et al*., 2006b). Also, it helps by reducing the susceptibility of low-density lipoprotein to oxidation (Grundy, 1986; Roche, 2001).

Consequently, the objective of this study was to evaluate the effect of full-fat high oleic (HO-FF) soybeans on broiler live performance, carcass and cut-up parts yield, and meat fatty acid composition in comparison to normal oleic extruded expeller (NO-EE) and normal oleic full-fat (NO-FF) soybeans.

Materials and Methods

All procedures involving the broilers used were approved by the North Carolina State University Institutional Animal Care and Use Committee.

Treatments

Five hundred forty chicks of Ross-708 (egg source: Pilgrim's Pride, Sanford, NC) were hatched feather-sexed, and males were placed in 30-floor pens (122 x 188 x 82 cm^3) with ten replicates per treatment. Pine shaving was used as litter. All the pens were supplied with one tubular feeder and one belt drinker, while supplemental feeders and drinkers were used for the first 7 d of the experiment. They were raised till the age of 47 days on the floor pens with three dietary treatments, including NO-EE, NO-FF, and HO-FF. All the chicks were raised in a poultry house with negative pressure tunnel ventilation, evaporative cooling pads, and a temperature-controlled environment.

Chickens received corn-soybean meal diets. The extruded soybean was produced in the same location under similar processing conditions. Foreign materials were removed by using the Eclipse 324 seed and grain cleaner (Seedburo, equipment company). Extrusion was conducted in a commercial feed mill, Mule City Feeds (Benson, NC, USA), by a single screw dry extrusion (InstaPro 2000 R, Iowa, USA) to produce full-fat soybean. The whole soybeans were extruded at a die temperature of 155 oC. Extruded expeller soybeans were produced by a different process of expelling, which was done after extrusion. During this process, extruded soybeans were mechanically pressed to extract the oil, and the resulting product had less oil than extruded soybeans. The nutrient and energy content of soybeans were obtained by near-infrared spectroscopy (NIRS) and wet chemistry. Five soybean source replicates were used for NIRS values, and an average value was used. Diets were formulated on digestible AA content and to be isoenergetic and isonitrogenous. They had identical digestible Lys, Thr, Val, TSAA, Ca, and available P in three feeding phases. The nutrient composition of soybean sources is shown in Table 1. The ingredient composition (%) of diets is presented in Table 2, while energy and nutrient content is presented in Table 3. One of three isocaloric and isonitrogenous crumble starter diets from 0 to 14 d was formulated (Concept 5 formulation) as 3,000 kcal/kg and 22.83 % CP, while the pelleted grower diet from 15 to 35 d with 3,100 kcal/kg and 20.70 % CP and pelleted finisher diet from 36 - 47 d with 3,200 kcal/kg and 19.04 % CP (Table 3) to meet or exceed NRC requirements for broilers (NRC, 1994). Starter and grower diets had ionophores.

All diets contained the same corn, dried distillers' grains with solubles (DDGS), and phytase. Nutrient analysis of these ingredients was performed before mixing each dietary phase (starter, grower, and finisher). Soybean contains phytate (a bound form of phosphorus in plants) and can interfere with the absorption of minerals. Phytase enzyme was added to diets to increase the overall availability of dietary phosphorus to chickens. Soybean subsamples were analyzed for mycotoxins (vomitoxin, aflatoxin, fumonisin, ochratoxin, T-2 toxin, and zearalenone), fatty acid, and proximate analysis. Levels of mycotoxins in soybean sub-samples were below the detection threshold for each analysis. All diets were crumbled and pelleted at 85ºC while corn particle size was kept between 700 to 800 µm for the starter and 800 to 900 µm for the grower and finisher. Water and feed were provided unrestricted to all broilers during the experiment.

Data and sample collection

Group body weight (BW), individual BW, and feed intake (FI) were recorded for each pen at 7, 14, 35, and 47 days of age, while BW gain and feed conversion ratio (FCR) and adjusted FCR (adjusted for mortality) were calculated. At 48 days, four broilers per replicate were selected randomly (40 chickens per treatment). Feed was withdrawn 12 h before termination, and selected broilers were processed at the NC State University processing plant (Raleigh, NC). Chickens were weighed before processing, stunned with electricity for 11 s, slaughtered by exsanguination, and 90 s period was provided to bleed. Carcass dressing was completed by removing the liver, gizzard, heart, oil gland, crop, proventriculus, lungs, and viscera. Once evisceration was completed, carcasses were air-chilled in the cooler for six h to start a manual deboning on stationary cones. Leg quarters, breast fillets (*Pectoralis major*), breast tenders (*Pectoralis minor*), wings, and racks with skin were removed and weighed. Subsequently, the *Pectoralis major* and *Pectoralis minor* muscles were collected and stored at -20° C till further analysis.

Meat quality was assessed by evaluating drip loss, cook loss, color, pH, and pectoral myopathies, including wooden breast (WB), white striping (WS), and *spaghetti muscle* (SM). Two experienced persons completed the myopathy scoring to evade subjective variations due to the evaluator. Drip loss was evaluated by weighing breast fillets and hanging them from a plastic hook in a refrigerator at 4 – 6 °C for 24 h. After the given time, each fillet was weighed carefully, and the difference was determined. Cook loss was evaluated by considering the breast fillets and cooking them, on aluminum pans, in a forced-air oven (SilverStar Southbend, Model SLES/10sc, gas type, NC, USA). Target internal temperature was 75 °C, achieved in approximately 35 mins and assessed with a Therma Plus thermocouple with a 10-cm needle temperature probe (ThermoWorks Model 221-071, UT, USA). After that, the oven was turned off, and the fillets were allowed to cool down to room temperature. They were weighed again to assess the weight difference before and after cooking.

The meat pH was determined by a portable pH meter (Oakton-Eutech Instruments® waterproof pH Tester 30) used on breast fillets at 6 and 24 h after processing. Meat values color (L* lightness, a* redness, and b* yellowness) of the breast were assessed by a calorimeter Minolta

Chroma Meter CR-400 (Konica Minolta Sensing, Inc., Japan). Two experienced people performed the sensory evaluation and scoring to identify the presence of WB (1-4), WS (0-3), or SM (presence or absence).

For fatty acid analysis, breast fillets (*Pectoralis major*) and breast tenders (*Pectoralis minor*) were collected and stored in the freezer till further analysis. The chicken breast samples were homogenized using a commercial food processor (Blixer Model 6, Robot Coupe, Jackson, MS, U.S.A.). The samples were extracted using a modified Folch procedure in which samples of 10 grams were weighed into 250 mL centrifuge bottles (Folch *et al*., 1957). The fat content of the original meat sample was quantified according to the equation:

Fat in samples (%) = Residue weight (g) / Sample weight (g) x 100

The fatty acid composition of samples was determined following methods outlined by Bannon *et al*. (1982). Gas-liquid chromatography was conducted using a PerkinElmer® AutoSystem XL gas chromatograph with an autosampler (PerkinElmer® Inc., Norwalk, CT, USA) and a BPX70 capillary column (SGE Technologies, Merseyside, UK) of 30 m length, 0.25 mm inside diameter, and 0.25 um film thickness. A commercial standard of fatty acid methyl esters (FIM-FAME-6, Matreya LLC, State College, PA, USA) was used to compare the retention times of compounds for identification. Quantitative analysis of following the identification and normalization of peaks was accomplished following Official Method Ce 1-62 of the American Oil Chemists' Society (AOCS, 2003).

Statistical analysis

Data was analyzed in a completely randomized design using two-way ANOVA, while mean separation was done using Tukey's or Student's t-tests at the significance level of alpha=0.05. All the percentage data were transformed, and data were analyzed using the JMP pro 15 software (SAS Institute, Inc., Cary, NC)**.**

Results

Live performance

Live performance results of broilers from 0 d to 7 d and 7 d to 14 d are shown in Table 4, while from 0 to 35 d and 47 d are shown in Table 5. Broilers fed with HO-FF were lighter ($P < 0.005$) than broilers fed NO-EE and NO-FF diets at 7 and 35 d, while no effect was observed at 47 d. However, on 14 d, broiler chickens of the HO-FF had greater BW than broilers fed the NO-FF diets. Dietary treatments had almost similar effects on broiler FCR and adjusted FCR. The HO-FF treatment broilers had poorer FCR ($P < 0.05$) compared to broilers of the NO-EE and NO-FF treatment groups at 7, 14, 35, and 47 d. There was no significant effect of treatments ($P > 0.05$) on feed intake at 7 and 47 d. However, on 14 and 35 d, broilers fed the HO-FF experimental diet consumed more feed ($P < 0.05$) than broilers fed the NO-FF diet, but less than broilers fed the NO-EE diet. There was no significant effect of treatment on flock uniformity and mortality at 47 d (Table 5).

Carcass and cut-up parts yield

Broiler carcass and cut-up parts yield (%) are shown in Table 6. Carcass yield was improved ($P < 0.05$) for broilers fed the NO-EE experimental diet in comparison to the HO-FF experimental diet (77.42 *vs.* 76.54%), while the NO-FF diet was intermediate (77.02%). There were no significant effects ($P > 0.05$) of dietary treatments on the cut-up parts yield, including legs, wings, *Pectoralis major*, *Pectoralis minor*, breast, and rack + skin. Also, no significant effects ($P > 0.05$) of SB sources were observed on fat and visceral organs (%) on broilers at 47 d (Table 7).

Meat quality and meat fatty acid profile

Breast meat pH was measured 6 and 24 h post-slaughter. Broilers fed the HO-FF experimental diet had ($P < 0.05$) the lowest breast pH (5.89) compared to the NO-EE and NO-FF treatment groups (5.90, and 5.94, respectively) 24 h post-slaughter. There were no other dietary treatment effects observed on any other meat quality parameters ($P > 0.05$) measured, which included breast color parameter (L, a, b), drip loss, and cooking loss (Table 8). There was a higher incidence ($P < 0.05$) of WB (score 1) for broilers fed the NO-FF diets in comparison to the other treatment groups. However, the SB source had no significant effect on WS and SM (Table 9).

Table 10 presents the effect of SB sources on the breast meat fatty acid profile (g fatty acid/ 100 g of all fatty acids). Broilers fed on HO-FF experimental diets had 54 to 86 % more oleic acid ($P < 0.001$) in their breast meat, while linoleic acid content was reduced ($P < 0.001$) by 42 to 57% as compared to the other two treatments. Other monounsaturated fatty acids like gondoic acid ($P < 0.001$), palmitoleic acid ($P = 0.001$), and erucic acid ($P < 0.05$) meat contents were also higher in broilers fed on HO-FF diets than other two treatments. Saturated fatty acids like myristic acid ($P < 0.001$), margaric acid ($P < 0.001$), palmitic acid ($P < 0.001$), stearic acid ($P < 0.001$), pentadecanoic acid; 15:0 ($P < 0.05$) and poly unsaturated fatty acid like linolenic acid ($P < 0.001$), alpha-linolenic acid ($P < 0.001$) meat contents were lower in broilers consuming HO-FF diet compared to NO-FF and NO-EE diets. No significant effect of diets was observed on meat content of pentadecanoic acid (15:1, cis), heptadecenoic acid, arachidic acid, eicosadienoic acid, dihomo-y-linolenic acid, eicosatrienoic acid, behenic acid, timnodonic acid and cerotic acid.

Discussion

Live performance

The NO-EE showed better BW and BW gain at 7, 14, and 35 d than NO-FF and HO-FF. At 47 d, the response was similar, but the effects were non-significant. It could be due to large values observed at 47 d, but the difference between these values was not very high. For example, BW for HO-FF and NO-FF was 3,545 and 3,522 g, respectively, while the difference between these values is just 23 g. Results showed that EE SB was a better source of protein and energy than the FFSB. In general, the extrusion process can cause some denaturation of some proteins and AA, so formulation for extruding rations should be done with increased density to compensate for losses during processing (Jones *et al*., 1995). However, in the current study, all diets were extruded, but only NO-EE was treated further in the expeller process, which is one of the reasons for the low oil and trypsin inhibitor content.

Clarke and Wiseman (2005, 2007) concluded that TIA content should not be more than 4.0 mg/g. In our experimental diets, TIA contents in all diets were under the maximum limit, but still, NO-FF and HO-FF have 0.48 to 1.31 mg/kg more TIA content than NO-EE, and it could be one of the factors influencing the effects on broiler live performance. Heger *et al*. (2016) concluded that even more than 4.0 mg/g of TI did not affect the growth performance; however, a linear improvement in feed efficiency has been observed when TIA decreased gradually below 1.0 mg/g without impairing growth performance, although there was excessive heat-damage to the protein fraction (Hoffmann *et al*., 2019). In the present experiment, the diets were formulated to be isoenergetic, but the energy content estimated may not be adequate and could be underestimated for both FFSB sources. Although the same extrusion technique was applied to all three soybean sources during the processing of SB, the expeller process was applied only to NO-EE soybean.

The ME value of the diets which have extruded whole soybean could be increased by pelleting the diets (Wiseman, 1984). McNab (1985) also demonstrated that the application of the extrusion technique offered the maximum energy value to processed whole SB when evaluated with other processing techniques.

The FCR was affected at all age periods except for 14 d. Although there were no effects on BW and FI at 47 d, a significant effect was observed for FCR at 47 d. It may be due to the small values of FCR, while the corresponding difference was large enough to be significant. For example, FCR for HO-FF and NO-EE was 1.603 and 1.532, while the difference between these values is 0.071. Leeson and Attech (1996) did not observe significant effects of the extrusion temperature on the FCR of broilers raised to three weeks. Subuh *et al*. (2002) concluded that extruded FFSB could replace the SE SBM without compromising BW, FCR, and mortality. Their study significantly affected BW and FCR at 42 d. Still, they processed SB by passing them through a roller mill and then extruding them without steam. It could suggest that the actual ME of the FFSB may not have been estimated correctly by the formula used to calculate the energy of this product (Jansen *et al*., 1979) and did not include the rolling of beans before extrusion. This step could increase cellular disruption and subsequent release of oil from individual cells.

In the present experiment, only carcass yield (%) was affected ($P < 0.05$) by the dietary treatments, while cut-up parts remained unaffected. Also, treatments did not significantly affect the relative weights of abdominal fat, liver, pancreas, intestine, gizzard + proventriculus, and spleen. The diets were formulated to be isocaloric and isonitrogenous, so it could be assumed if the ratio of nutrients to energy in a diet remained the same. No adverse effects on these carcass traits could be detected. In this experiment, at 47 d, the FI for NO-EE was intermediate, while the highest was for HO-FF. This feed intake can potentially change the consumption of AA and energy. However, the difference in FI between HO-FF (maximum FI) and NO-FF (minimum FI) was only 261 g considering the age and total FI. Also, FFSB provides more energy than the EESB or soybean meal (SBM) due to its fat content and can be protected from oxidation and rancidity for the presence of natural antioxidants, including Vitamin E and selenium-dependent enzyme glutathione peroxidase in the seed (North and Bell, 1990).

In a study conducted by Subuh *et al*. (2002), the SBM was replaced with extruded FFSB at 0/100, 25/75, 50/50, 75/25, and 100/0 (wt/wt). Still, no significant effect was observed on the dressing percentage or abdominal fat percentage on broilers raised at 42 d. Even increasing the dietary energy level did not adversely affect these traits. However, crude protein and AA levels remained constant during their study with dietary energy levels, and no adverse effect on carcass fatness was observed. Alsaftli *et al*. (2015) also observed no significant effect of extruded FFSB on carcass yield, breast and thigh parts including bone, and relative liver weight to live weight of female turkeys when SBM was replaced with 10, 15, and 20% extruded FFSB. The TIA factors could reduce the nutrient digestibility in SB, and in turn, bile acid excretion could increase, which ultimately reduces the digestibility of fats (Anderson-Haferman *et al*., 1992). Zollitsch *et al*. (1997) replaced the fat source with alternative sources and concluded that there was no significant difference in dressing, legs, breast meat, and abdominal fat.

A reduction in broiler chicken BW at 42 d was observed when fed on diets containing high levels (22.5%) of extruded FFSB in replacement of dehulled SBM (Mirghelenj *et al*., 2013) while Milczarek *et al*. (2017) showed that inclusion of extruded FFSB in broiler diets as a partial substitute of SBM (30% in starter and 50% in grower and finisher mixer diets) gave a similar broiler BW with a similar feed consumption level. Replacing the SBM with EE SB cake at 25, 50, and 100% showed increased FI, decreased BW, and increased FCR (Śliwa and Brzóska, 2018).

The HO-FF was found to increase oleic fatty acid in the diet and consequently in broiler meat. In an experiment conducted by Toomer *et al*. (2020), the effect of high oleic peanuts was studied on broiler live performance as an alternative protein ingredient. Broilers fed on a high oleic peanut diet had less BW and poor FCR than the control treatment at 42 d. However, no effects of dietary treatments was observed on FI. Rodríguez *et al*. (2005) used the high oleic acid sunflower seeds (HOASS) in different proportions in the basal diets of broiler chickens. Broilers fed on diets containing 100 and 200 g of HOASS achieved less BW and FCR at 42 d than those without HOASS. However, no significant effect of dietary treatment was observed on FI. The energy level in the diets is considered as FI regulatory factor, and the diets used in this experiment were isocaloric. So, the effects on BW can be attributed to diet composition, not due to differences in FI. Few other studies in which high-oleic SBM was evaluated with non-transgenic and commercial SBM in broilers, laying hens, and swine, the animal growth reaction was similar to animal nutrition equivalency (McNaughton *et al*., 2007; Mejia *et al*., 2010; Knowlton, 2022).

Carcass and cut-up part yields

In the past years, broiler chicken products were sold as the whole carcass. But, in recent years, due to more consumer demand for chicken parts than whole chicken, there has been more focus on broiler production with better carcasses, cut-up yields, and meat quality (Gous *et al*., 1999; Toomer *et al*., 2020). Powell *et al*. (2011) did not detect a significant difference in the carcass weight of slaughtered chickens after introducing EE SB as the only source of protein. In one experiment conducted by Janocha *et al*. (2022) showed that replacing the SE SBM with EE SB and extruded FFSB in broiler diets increased ($P < 0.05$) pre-slaughter BW at 42 d. Although there was no effect of dietary treatment on dressing percentage, broilers fed on the SBM, and EE SB cake showed a higher share of breast and leg muscles (by 4.74% and 7.54%) and a lower share of abdominal fat (by 31.1%) and skin with subcutaneous fat (by 18.8% and 13.4%) in comparison with chickens from the extruded FFSB group ($P < 0.05$). Jahanian and Rasouli (2016) also demonstrated that replacing all SBM with extruded FFSB significantly increased BW and feed consumption, but FCR was lower in 5-week-old chickens.

The present study observed no effect of dietary treatments on abdominal fat, liver, pancreas, intestine, gizzard, proventriculus, and spleen. Pacheco *et al*. (2014) did not observe the effect of extruded SB seeds on gizzard weight percentage in the chicken carcass. Śliwa and Brzóska (2018) did not observe any impact on the share of giblets (heart, liver, and gizzard) when on average, 10, 18, and 40% of SB expeller cake was used in broiler chicken feed. In a study by Peckman (2020), broilers fed on commodity SBM, and oil had heavier liver weight (in g) than those fed on high oleic SBM and oil at 42 d. It can be because of the more physiological need for heavier broilers fed on commodity SBM. A moderate, positive correlation exists between broiler liver weight and BW at 42 d (Gaya *et al*., 2006).

Meat quality parameters

Meat quality is a complicated term to explain the various intrinsic and extrinsic variables pushing the customer's appreciation of a meat product. Broiler meat yield has grown to new levels, and it is due to improvements in genetics and production practices that were adopted in the poultry industry. However, success in increased output has led to more focus on considering broiler meat quality improvement (Mir *et al*., 2017). Janocha *et al*. (2022) did not find any significant pH effect on the breast muscles of broilers after 15 mins of slaughtering when fed on SE SBM, extruded expeller, and FFSB. However, there were substantial results on thigh muscles after 24 h of slaughtering. The pH range was 5.81 for extruded FFSB while 5.88 and 5.95 for EE SB cake and SE SBM, respectively. The optimum pH after 24 h of slaughtering is considered in the range of

5.35 – 6.10, which indicates the meat evaluated is normal. The results are close to those reported by Rycielska *et al*. (2010). The results in the current experiment were in accordance with other experiments. No significant pH effect was observed on breast muscle after six h of slaughtering, but after 24 h, there was a significant pH effect within the range of typical pH values. The change in pH may be due to postmortem metabolism (glycolysis) or a change in dripping loss over time.

The two most severe anomalies in chicken breast muscle reported recently are WB and WS (Kuttappan *et al*., 2016; Meloche *et al*., 2018; Petracci *et al*., 2019), which lead to unattractive appearance, carcass downgrading, condemnation, and reduced protein functionality in processed products (Mudalal *et al*., 2014; Petracci *et al*., 2014, 2019; Tijare *et al*., 2016). However, despite the increased incidence of WB and WS in broilers, the exact reason for these muscle myopathies is still unknown (Khan *et al*., 2021). The same is the case with SM, a relatively new muscle myopathy, and the reason is also unknown. In the current study, the WB score was measured on a score range of 1 to 4, while WS was measured on a scale of 0 to 3. SM was reported as present or absent. No significant effect was observed ($P > 0.05$) on myopathies, including WB, WS, and SM incidence, except WB, score 1.

Fatty acids profile

The major fatty acids in chicken meat include oleic acid, palmitic acid, linoleic acid, stearic acid, and arachidonic acid (Zhao *et al*., 2011; Amorim *et al*., 2016). The dietary requirement for essential fatty acids for poultry is usually related only to linoleic acid, and 10g/kg is believed to be satisfactory for optimal performance (NRC, 1994). This quantity is expected to be present by the native triglycerides in the diet (Zollitsch *et al*., 1997). In the current experiment, broilers fed on HO-FF had a better oleic acid profile in the *Pectoralis* muscles than the other two treatments. Janocha *et al*. (2022) concluded that extruded full-fat genetically modified (GM) SB could be recommended in broiler diets as it could best modify the lipid profile of broiler muscles. In their study with all normal oleic sources of soybean, extruded FFSB (non-GM), used as the protein in feed rations for broiler chickens, contributed to a significant ($P < 0.05$) decrease in palmitic, stearic, and saturated fatty acids in breast muscle as compared to the EE SB cake (non-GM) and SE SBM (GM). They also reported a significant ($P < 0.05$) lowest content of oleic acid and monounsaturated fatty acid (MUFA) and the highest content of linoleic acid, linolenic acid, and polyunsaturated fatty acids (PUFA) in the muscles of broilers fed on extruded FFSB than SBM and EE SB cake.

The dietary value of poultry meat is due to its proximate composition and share of fatty acids (Szkucik *et al*., 2009; Milczarek and Osek, 2019; Janocha *et al*., 2021). Milczarek and Osek (2019) demonstrated a significant increase in the linoleic acid and linolenic acid content in the muscles of chickens feeding on diets containing extruded FFSB, and many authors have pointed toward this relationship. In an experiment conducted by Slaughter *et al*. (2019), broiler chickens were raised on corn-soy diets, which include commercial SBM and oil and a corn-soy diet with high oleic SBM and oil. At 42 d, breast and thigh meat was analyzed for meat fatty acids. Diet affects ($P < 0.001$) the fatty acid composition of meat. In *Pectoralis major,* HO treatment increased 55 and 84% the proportion of oleic acid, while linoleic acid was reduced by 42 and 54 % to NO-EE and NO-FF, respectively. This study was in accordance with our current experiment. Other MUFAs, for example, gondoic acid, palmitoleic acid (16:1, trans), and erucic acid, were also higher in meat of broilers fed on HO-FF diet. Dietary monosaturated fatty acids are linked with reducing risk factors associated with metabolic syndrome and cardiovascular diseases. They foster a healthy blood lipid profile, mediates blood pressure, enhance insulin sensitivity, controls blood glucose level, and decrease the risk of obesity (Gillingham *et al*., 2011).

Generally, saturated fatty acids are found in meat, animal fat, and butterfat and have no double bonds within the carbon backbone and are occupied with maximum hydrogen molecules (Milićević *et al.*, 2014). Saturated fatty acids like myristic acid and palmitic acid may increase the total and low-density lipoprotein (LDL) cholesterol which can increase the risk of cardiovascular diseases (Lichtenstein *et al*., 2006a). These fatty acid concentrations were reduced in meat samples obtained from chickens fed on HO-FF. Lignoceric acid is a very long saturated fatty acid, and it was significantly lower in meat (*Pectoralis major* only) of broilers fed on HO-FF diets. The presence of saturated fatty acids in chicken meat significantly relies on their availability in chicken diets and/or production in the liver (Sheehy *et al*., 1993). In humans, it has been observed that almost 5% isocaloric replacement of saturated fatty acids by oleic acid can decrease the coronary heart disease risk by 20-40%, primarily via LDL-cholesterol reduction (Kris-Etherton, 1999). Other risk factors associated with heart diseases, such as thrombogenesis, *in vitro* LDL oxidative susceptibility, and insulin sensitivity, were also lowered by oleic acid (Wahrburg, 2004). In many countries, the consumption of saturated fatty acids is more than recommended allowance (Hulshof *et al*., 1999). Increasing oleic acid intake may be helpful because it restricts the intake of saturated fat (Lopez-Huertas, 2010). The digestion of unsaturated fatty acids inhibits the production of saturated fatty acids in the liver due to the inhibition of hepatic 9-desaturase complex activity, which ultimately lower body fat composition in chickens (Sim and Qi, 1995). Additionally, research has revealed that chickens on relatively high oleic acid diets (MUFA) have less susceptibility to meat oxidation than chickens fed on diets with relatively high PUFAs and indicated a more favorable nutritional profile (Rebolé *et al*., 2006).

Breast meat analyzed from broilers that were fed on high-oleic peanuts showed a higher level of MUFA (55%) than those (35%) fed on a traditional corn-soy diet (Toomer *et al*., 2020).

These results support the existing idea that dietary fatty acid composition is positively correlated to meat fatty acid composition in monogastric (Semwogerere *et al*., 2019).

Conclusion

Processing soybeans can affect broiler chickens' live performance and carcass yield. Broilers fed on HO-FF had low performance and carcass yield compared to NO-EE and NO-FF. However, dietary treatments did not affect cut-up parts and visceral organs (%). The same was true for meat quality parameters such as color, dripping, and cooking loss except pH after 24 hrs. However, broilers fed on HO-FF had significantly higher contents of oleic acid, 55% on average, in their breast meat than broilers fed on NO-EE and NO-FF.

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Table 1. Nutrient composition of soybean sources used in experiment.

Nutrient	**SE SBM**	**NO-EE SB**	**Full-fat soybean**	
			NO	**HO**
Protein, crude, %	47.15	43.80	38.31	38.18
Fat, crude, %	2.57	8.99	18.21	18.21
Fiber, crude, %	3.77	5.27	6.10	6.10
Calcium, %	0.34	0.20	0.28	0.28
Phos. total, %	0.63	0.57	0.48	0.48
Ash, %	6.83	6.41	5.52	5.52
Phos. available, %	0.23	0.19	0.16	0.16
Lysine, %	2.83	2.66	2.34	2.40
TSAA, %	0.64	1.21	1.06	1.13
Threonine, %	1.81	1.68	1.49	1.49
Valine, %	2.22	2.07	1.82	1.82
Leucine, %	3.52	3.33	2.86	2.80
Tryptophan, %	1.29	0.59	0.51	0.50
Trypsin inhibitor, mg/g	0.95	7.46	11.02	11.02
Dig. Lysine, %	2.57	2.36	2.03	2.09
Dig. Methionine, %	0.56	0.51	0.44	0.44
Dig. Cystine, %	0.55	0.49	0.40	0.45
Dig. TSAA, %	1.12	1.00	0.84	0.89
Dig. Threonine, %	1.52	1.41	1.24	1.24
Dig. Tryptophan, %	0.57	0.52	0.43	0.41
Dig. Isoleucine, %	1.93	1.82	1.51	1.49
Dig. Leucine, %	3.20	2.97	2.50	2.45
Dig. Valine, %	1.97	1.80	1.55	1.55
Dig. Histidine, %	1.08	0.99	0.87	0.88
Dig. Arginine, %	3.20	2.91	2.48	2.58
Dig. Phenylalanine, %	2.16	1.96	1.69	1.68
Palmitic acid C16:0, %	0.67	0.80	1.93	1.20
Palmitoleic acid C16, %	0.00	0.01	0.03	0.02
Stearic acid C18:0, %	0.17	0.26	0.61	0.48
Oleic acid C18:1, %	0.68	1.40	3.12	11.13
Linoleic acid C18:2, %	2.65	3.79	9.55	1.71
Linolenic acid C18:3, %	0.41	0.59	1.45	0.02

Abbreviations: TSAA, total sulfur amino acids; SE SBM, solvent extracted soybean meal; NO-EE SB, normal oleic extruded expeller soybean; NO, normal oleic; HO, high oleic

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

Table 2. Ingredient composition of experimental diets.

Ingredient (%)	Starter (1 – 14 d)			Grower (15 – 35 d)			Finisher (36 - 47 d)		
	NO-EE	Full fat soybean		NO-EE	Full fat soybean		NO-EE	Full fat soybean	
		NO	HO		NO	HO		NO	HO
Corn	51.41	50.99	50.84	56.43	55.57	55.37	59.80	58.96	58.77
SE SBM	6.93	16.50	16.50	5.00	6.91	6.89	5.00	5.06	5.00
NO-EE SB	32.23	0.00	0.00	28.92	0.00	0.00	24.60	0.00	0.00
NO-FF SB	0.00	25.14	0.00	0.00	30.85	0.00	0.00	28.20	0.00
HO-FF SB	0.00	0.00	25.38	0.00	0.00	31.12	0.00	0.00	28.50
DDGS	3.00	3.00	2.95	3.00	3.00	3.00	3.00	3.00	3.00
Poultry fat	1.96	0.00	0.00	2.90	0.00	0.00	4.16	1.42	1.42
Limestone fine	1.44	1.35	1.35	1.17	1.08	1.08	1.07	0.99	0.99
Dicalcium phosphate	1.13	1.11	1.11	0.94	0.94	0.94	0.81	0.81	0.81
DL-Methionine	0.38	0.38	0.37	0.30	0.32	0.30	0.28	0.29	0.27
Sodium bicarbonate	0.26	0.27	0.27	0.20	0.21	0.20	0.25	0.26	0.25
L-Lysine	0.27	0.28	0.25	0.19	0.20	0.17	0.18	0.19	0.17
Salt, plain (NaCl)	0.29	0.27	0.28	0.31	0.29	0.30	0.27	0.26	0.26
Mineral premix[1]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Choline chloride 60	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.18
L-Threonine	0.16	0.15	0.15	0.09	0.09	0.08	0.07	0.07	0.07
Vitamin premix[2]	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
Coccidiostat[3]	0.05	0.05	0.05	0.05	0.05	0.05	0.00	0.00	0.00
Phytase[4]	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02

Abbreviations: SE SBM, solvent extracted soybean meal; SB, soybean; NO-EE, normal oleic extruded expeller; NO-FF, normal oleic full-fat; HO-FF, high oleic full-fat; DDGS, dried distillers' grains with solubles; NO, normal oleic; HO, high oleic

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

[1] Trace minerals provided per kg of premix: manganese (Mn SO4), 60 g; zinc (ZnSO4), 60 g; iron (FeSO4), 40 g; copper (CuSO4), 5 g; iodine (Ca(IO3)2),1.25 g.

[2] Vitamins provided per kg of premix: vitamin A, 13,227,513 IU; vitamin D3, 3,968,253 IU; vitamin E, 66,137 IU; vitamin B12, 39.6 mg; riboflavin, 13,227 mg; niacin, 110,229 mg; d-pantothenic acid, 22,045 mg; menadione, 3,968 mg; folic acid, 2,204 mg; vitamin B6, 7,936 mg; thiamine, 3,968 mg; biotin, 253.5 mg.

[3] Coban® 90 (Monensin), Elanco Animal Health, Greenfield, IN, at 500 g/ton.

[4] Natuphos E® (500 FTU/kg, 50 g/ton FTU).

Table 3. Energy and nutrient content of experimental diets.

Nutrient Name	Starter (1 – 14 d)			Grower (15 – 35 d)			Finisher (36 – 47 d)		
	NO-EE	Full fat soybean		NO-EE	Full fat soybean		NO-EE	Full fat soybean	
		NO	HO		NO	HO		NO	HO
M.E. Poultry, kcal/kg	3.000	3.000	3.000	3.100	3.100	3.100	3.200	3.200	3.200
Protein, crude, %	22.83	22.83	22.83	20.70	20.70	20.70	19.04	19.04	19.04
Fat, crude, %	7.39	7.36	7.39	8.18	8.34	8.38	9.18	9.35	9.39
Fiber, crude, %	2.93	3.12	3.13	2.76	3.18	3.19	2.59	3.00	3.01
Calcium, %	1.00	1.00	1.00	0.85	0.85	0.85	0.78	0.78	0.78
Phos. total, %	0.57	0.56	0.57	0.51	0.51	0.51	0.47	0.47	0.47
Ash, %	5.65	5.52	5.53	4.95	4.83	4.84	4.50	4.40	4.41
Phos. available, %	0.46	0.46	0.46	0.42	0.42	0.42	0.39	0.39	0.39
Lysine, %	1.41	1.42	1.42	1.22	1.23	1.23	1.11	1.12	1.12
TSAA, %	1.05	1.06	1.06	0.93	0.94	0.95	0.87	0.88	0.88
Threonine, %	0.99	1.00	1.00	0.86	0.86	0.86	0.87	0.88	0.88
Valine, %	1.05	1.05	1.06	0.96	0.96	0.97	0.88	0.89	0.89
Leucine, %	1.91	1.89	1.88	1.78	1.76	1.74	1.67	1.65	1.64
Tryptophan, %	0.27	0.27	0.27	0.24	0.24	0.24	0.22	0.22	0.22
Trypsin inhibitor, mg/g	2.47	2.93	2.95	2.21	3.47	3.50	1.88	3.16	3.19
Dig. Lysine, %	1.28	1.28	1.28	1.09	1.09	1.09	0.99	0.99	0.99
Dig. Methionine, %	0.67	0.67	0.66	0.58	0.59	0.57	0.53	0.54	0.53
Dig. Cystine, %	0.29	0.28	0.29	0.26	0.26	0.27	0.25	0.24	0.25
Dig. TSAA, %	0.95	0.95	0.95	0.84	0.84	0.84	0.78	0.78	0.78
Dig. Threonine, %	0.86	0.86	0.86	0.73	0.73	0.73	0.66	0.66	0.66
Dig. Tryptophan, %	0.24	0.23	0.23	0.21	0.20	0.20	0.19	0.18	0.18
Dig. Isoleucine, %	0.88	0.86	0.85	0.79	0.77	0.76	0.72	0.70	0.70
Dig. Leucine, %	1.83	1.81	1.79	1.62	1.58	1.57	1.52	1.49	1.48
Dig. Valine, %	0.95	0.95	0.95	0.84	0.83	0.83	0.77	0.77	0.77
Dig. Histidine, %	0.50	0.50	0.50	0.47	0.47	0.48	0.44	0.44	0.44
Dig. Arginine, %	1.37	1.36	1.39	1.23	1.21	1.25	1.11	1.10	1.13
Dig. Phenylalanine, %	1.04	1.04	1.04	0.91	0.90	0.90	0.84	0.83	0.83
Palmitic acid C16:0, %	0.30	0.60	0.42	0.26	0.64	0.42	0.23	0.58	0.38
Palmitoleic acid C16, %	0.00	0.01	0.01	0.01	0.01	0.01	0.00	0.01	0.01
Stearic acid C18:0. %	0.10	0.18	0.15	0.08	0.20	0.16	0.07	0.18	0.15
Oleic acid C18:1, %	0.50	0.90	2.94	0.44	1.01	3.51	0.38	0.91	3.20
Linoleic acid C18:2, %	1.41	2.48	0.879	1.23	3.13	0.71	1.06	2.83	0.62
Linolenic acid C18:3, %	0.22	0.43	0.19	0.19	0.48	0.18	0.17	0.43	0.16

Abbreviations: NO-EE, normal oleic extruded expeller soybean; NO, normal oleic; HO, high oleic

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

Table 4. Effect of soybean sources on the live performance of Ross 708 male broilers from 0 d to 7 d and 0 d to 14 d of age on floor pens.

Treatment	**BW**	**BWG**	**FI**	**FCR**	**Adj FCR***
	------------- (g)	-------------		------- (g:g)	-------
0 - 7 days					
NO-EE SB	176^{a}	132^{a}	152	1.152^{b}	1.152^{b}
NO-FF SB	167^{b}	123^{b}	147	1.199^{ab}	1.199^{ab}
HO-FF SB	166^{b}	122^{b}	149	1.225^{a}	1.225^{a}
SEM	2	2	2	0.019	0.019
CV%	4.10	5.51	3.49	5.02	5.02
P-values	0.005	0.005	0.122	0.033	0.033
0 - 14 days					
NO-EE SB	526^{a}	483^{a}	558^{a}	1.146	1.146
NO-FF SB	497^{b}	454^{b}	529^{b}	1.155	1.155
HO-FF SB	508^{b}	465^{b}	541^{ab}	1.165	1.165
SEM	4	4	6	0.007	0.007
CV%	2.37	2.58	3.51	1.81	1.81
P-values	<0.001	<0.001	0.008	0.150	0.150

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean; BW, body weight; BWG, body weight gain; FI, feed intake; FCR, feed conversion ratio

[a,b] Means that do not share superscript letters in a column are significantly different ($P < 0.05$) by Tukey's test.

*FCR was adjusted by mortality weights.

Table 5. Effect of soybean sources on the live performance of Ross 708 male broilers from 0 d to 35 d and 0 d to 47 d of age on floor pens.

Treatment	BW	BWG	FI	FCR	Adj FCR*	Uniformity	Total mortality
0 – 35 days	------------- (g) -------------			------ (g:g) ------		--- CV% ---	--- % ---
NO-EE SB	$2,494^{a}$	$2,449^{a}$	$3,306^{a}$	1.350^{b}	1.350^{b}		
NO-FF SB	$2,404^{b}$	$2,360^{b}$	$3,178^{b}$	1.347^{b}	1.347^{b}		
HO-FF SB	$2,400^{b}$	$2,356^{b}$	$3,272^{ab}$	1.389^{a}	1.389^{a}		
SEM	28	28	34	0.006	0.006		
CV%	3.59	3.65	3.33	1.5	1.5		
P-values	0.037	0.04	0.036	<0.001	<0.001		
0 – 47 days							
NO-EE SB	3603	3,558	5,568	1.532^{b}	1.532^{b}	13.11	3.89
NO-FF SB	3522	3,477	5,416	1.537^{ab}	1.537^{ab}	12.42	3.33
HO-FF SB	3545	3,499	5,677	1.603^{a}	1.603^{a}	11.11	6.11
SEM	36.03	36.31	89.37	0.019	0.019	0.76	1.77
CV%	3.15	3.21	5.09	3.78	3.77	10.69	
P-values	0.291	0.295	0.136	0.027	0.026	0.177	0.467

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean; BW, body weight; BWG, body weight gain; FI, feed intake; FCR, feed conversion ratio

[a,b] Means that do not share superscript letters in a column are significantly different ($P < 0.05$) by Tukey's test

*FCR was adjusted by mortality weights.

Table 6. Effect of soybean sources on carcass and cut-up parts yield (%) of Ross 708 male broilers at 47 days of age.

Treatment	**Carcass**	**Cut-up parts**					
		Legs	**Wings**	***Pectoralis major***	***Pectoralis minor***	**Breast**	**Rack+skin**
	---------- % ----------						
NO-EE SB	77.42^{a}	30.13	9.35	32.04	6.51	38.88	21.58
NO-FF SB	77.02^{ab}	30.84	9.42	31.43	6.68	38.08	21.61
HO-FF SB	76.54^{b}	30.63	9.40	31.30	6.65	37.94	22.02
SEM	0.22	0.22	0.10	0.30	0.07	0.31	0.25
CV%	1.52	2.81	2.73	3.52	4.67	3.03	3.27
Source of variation	---------- *P*-values ----------						
Treatment	0.027	0.076	0.885	0.193	0.249	0.099	0.383

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

[a-b] Means in a column not sharing a common superscript are significantly different ($P < 0.05$) by Student *t* or Tukey's test.

Table 7. Effect of soybean sources on fat and visceral organs (%) of Ross 708 male broilers at 47 days of age.

Treatment	Abdominal fat	Liver	Pancreas	Intestine	Gizzard + Proventriculus	Spleen
	---------------------------------- % ----------------------------------					
NO-EE SB	1.35	1.55	0.16	2.88	1.63	0.12
NO-FF SB	1.36	1.59	0.18	3.04	1.61	0.12
HO-FF SB	1.36	1.62	0.18	2.86	1.65	0.12
SEM	0.10	0.05	0.01	0.09	0.06	0.01
CV%	24.29	5.85	7.72	6.86	8.51	12.35
Source of variation	------------------------------ *P-values* ---------------------------					
Treatment	0.910	0.663	0.093	0.337	0.887	0.942

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

Table 8. Effects of soybean sources on breast meat pH and color parameters of Ross 708 male broilers at 47 days of age.

Dietary treatment	pH		Color parameters			Dripping loss	Cooking loss
	6 h	24 h	L	*a*	*b*		
						----- % -----	
NO-EE SB	5.81	5.90^{ab}	48.26	2.36	5.52	1.38	17.95
NO-FF SB	5.84	5.94^{a}	47.66	2.33	5.00	1.40	18.03
HO-FF SB	5.80	5.89^{b}	48.15	2.10	5.44	1.41	18.87
SEM	0.02	0.01	0.41	0.17	0.20	0.10	0.46
CV%	1.50	1.48	4.61	37.16	21.94	16.13	8.61
Source of variation	---------------------------------- *P* values ------------------------------						
Treatment	0.268	0.045	0.559	0.504	0.168	0.912	0.456

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

[a,b] Means that do not share superscript letters in a column are significantly different ($P < 0.05$) by Tukey's test

Table 9. Effect of soybean sources on the probability (0-1) of wooden breast (WB) occurrence and severity (scores 1-4), probability (0-1) of white-stripping occurrence and severity (scores 0-3) and the incidence (Yes/No) of spaghetti muscle of Ross 708 male broilers at 47 days of age.

Treatment	**WB Average score**	**WB Score**				**WS Score**				**SP incidence (%)**	
		1	**2**	**3**	**4**	**0**	**1**	**2**	**3**	**Yes**	**No**
NO-EE SB	2.85	2.50^{b}	35.00	37.50	25.00	2.50	32.50	37.50	27.50	15.00	85.00
NO-FF SB	2.48	17.50^{a}	30.00	40.00	12.50	10.00	42.50	22.50	25.00	10.00	90.00
HO-FF SB	2.60	5.00^{b}	42.50	40.00	12.50	12.50	40.00	37.50	10.00	22.50	77.50
SEM	0.14	0.04	0.08	0.08	0.06	0.04	0.08	0.07	0.06		
Source of variation		--- *P*-value -----------------------------------									
Treatment		0.039	0.503	0.966	0.239	0.188	0.630	0.242	0.092	0.305	

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

$^{a\text{-}b}$ Means in a column not sharing a common superscript are significantly different ($P < 0.05$) by Student *t* or Tukey's test.

Table 10. Effect of soybean sources on the profile of fatty acids in *Pectoralis* muscles of broilers raised till 47 days of age.

Fatty acids %	***Pectoralis major***			**SEM**	**CV%**	***P*-value**	***Pectoralis minor***			**SEM**	**CV%**	**P-value**
	NO-EE SB	**NO-FF SB**	**HO-FF SB**				**NO-EE SB**	**NO-FF SB**	**HO-FF SB**			
Oleic acid (18:1, cis)	31.50^{b}	26.57^{c}	48.85^{a}	0.50	6.2	<0.001	33.27^{b}	27.50^{c}	51.33^{a}	0.36	3.3	<0.001
Linoleic acid (18:2, cis)	25.66^{b}	32.61^{a}	14.87^{c}	0.33	5.7	<0.001	26.72^{b}	34.64^{a}	14.85^{c}	0.34	3.8	<0.001
Palmitic acid (16:0)	19.83^{a}	17.95^{b}	17.07^{c}	0.19	3.8	<0.001	20.3^{a}	17.98^{b}	17.26^{c}	0.17	3.4	<0.001
Stearic acid (18:0)	6.69^{a}	6.73^{a}	5.58^{b}	0.11	7.4	<0.001	6.35^{a}	6.21^{a}	5.37^{b}	0.08	7.9	<0.001
Palmitoleic acid (16:1, cis)	3.48^{a}	2.12^{c}	2.56^{b}	0.09	16.3	<0.001	3.92^{a}	2.37^{c}	2.80^{b}	0.10	16.4	<0.001
Arachidonic acid (20:4, n6)	3.10^{a}	3.25^{a}	2.37^{b}	0.19	33.4	0.012	1.90	2.12	1.95	0.12	33.0	0.405
α-Linolenic acid (18:3,n3)	1.78^{b}	2.98^{a}	1.25^{c}	0.05	13.1	<0.001	1.97^{b}	3.43^{a}	1.35^{c}	0.05	10.1	<0.001
Pentadecanoic acid (15:1, cis)	1.21	1.23	1.09	0.08	42.9	0.484	0.69	0.77	0.82	0.06	42.2	0.301
Myristic acid (14:0)	0.41^{a}	0.33^{b}	0.32^{b}	0.01	12.1	<0.001	0.42^{a}	0.33^{b}	0.31^{b}	0.01	10.6	<0.001
Margaric acid (17:0)	0.27^{b}	0.30^{a}	0.20^{c}	0.01	19.8	<0.001	0.27^{b}	0.31^{a}	0.20^{c}	0.01	9.9	<0.001
Elaidic acid (18:1, trans)	0.07^{a}	0.02^{ab}	0.00^{b}	0.01	215.7	0.008	0.02	0.01	0.03	0.01	294.6	0.461
Linolenic acid (18:3,n6)	0.26^{a}	0.24^{a}	0.20^{b}	0.01	13.9	<0.001	0.28^{a}	0.26^{a}	0.20^{b}	0.01	13.7	<0.001
Gondoic acid (20:1)	0.28^{b}	0.24^{c}	0.42^{a}	0.01	19.4	<0.001	0.28^{b}	0.24^{c}	0.41^{a}	0.01	20.5	<0.001
Lignoceric acid (24:0)	0.92^{a}	0.85^{a}	0.67^{b}	0.05	36.6	0.01	0.56	0.56	0.49	0.03	27.6	0.347
Lauric acid (12:0)	0.01	0.00	0.00	0.00	171.7	0.2	0.02^{a}	0.01^{b}	0.01^{ab}	0.00	87.2	0.010

Table 10 (continued).

Myristoleic acid (14:1, cis)	0.09^{a}	0.04^{b}	0.06^{b}	0.01	51.1	<0.001	0.10^{a}	0.06^{c}	0.08^{b}	0.00	24.9	<0.001
Pentadecanoic acid (15:0)	0.12^{a}	0.12^{a}	0.08^{a}	0.01	55.7	0.039	0.09^{ab}	0.10^{a}	0.07^{b}	0.01	51.0	0.018
Palmitoleic acid (16:1, trans)	0.34^{a}	0.23^{b}	0.41^{a}	0.03	42.8	0.001	0.34^{b}	0.26^{b}	0.47^{a}	0.03	36.9	<0.001
Heptadecenoic acid (17:1, cis)	0.35	0.345	0.37	0.02	46.6	0.782	0.26	0.26	0.30	0.02	40.0	0.120
Arachidic acid (C 20:0)	0.09	0.09	0.08	0.01	58.9	0.765	0.09	0.11	0.09	0.01	31.6	0.494
Eicosadienoic acid (20:2)	0.30	0.28	0.17	0.04	70.9	0.077	0.22	0.24	0.14	0.03	64.3	0.064
Dihomo-y-linolenic acid (20:3,n6)	0.13	0.20	0.15	0.03	106.4	0.288	0.10	0.15	0.14	0.03	98.9	0.378
Eicosatrienoic acid (20:3,n3)	0.45	0.42	0.41	0.03	24.5	0.573	0.33	0.34	0.34	0.01	20.9	0.786
Behenic acid (22:0)	0.00	0.00	0.01	0.00	305.0	0.055	0.01	0.01	0.01	0.00	190.3	0.546
Erucic acid (22:1, cis)	0.00^{b}	0.00^{b}	0.01^{a}	0.00	298.0	0.002	0.00^{b}	0.00^{b}	0.02^{a}	0.00	217.1	0.014
Timnodonic acid (20:5, n3)	0.29	0.27	0.27	0.05	101.9	0.955	0.14	0.10	0.17	0.02	44.7	0.051
Cerotic acid (26:0)	0.02	0.01	0.01	0.00	188.2	0.16	0.017^{ab}	0.02^{a}	0.01^{b}	0.00	110.1	0.010
Clupanodonic acid (22:6)	0.63^{ab}	0.75^{a}	0.57^{b}	0.05	40.5	0.039	0.37^{b}	0.52^{a}	0.42^{ab}	0.04	41.7	0.036
Others	1.37	1.58	1.48	0.10	42.0	0.364	0.90^{b}	1.05^{ab}	1.17^{a}	0.05	33.6	0.007
O/L	1.23^{b}	0.82^{c}	3.30^{a}	0.06	10.0	<0.001	1.25^{b}	0.80^{c}	3.43^{a}	0.06	9.6	<0.001

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

$^{a\text{-}c}$ Means that do not share superscript letters in a row are significantly different ($P < 0.05$) by Tukey's test.

EXTRA TABLES

Table 11. Effect of soybean sources on body weight at the processing age (47 d) and during the processing of Ross 708 male broilers.

Treatment	**Live BW**	**BW after evisceration**	**BW after cooling**	**Carcass yield**
	---------------------- (g)	----------------------		--% --
NO-EE SB	3,791^{a}	3,255^{a}	2,935^{a}	77.42^{a}
NO-FF SB	3,652^{b}	3,131^{b}	2,813^{b}	77.02^{ab}
HO-FF SB	3,629^{b}	3,094^{b}	2,769^{b}	76.54^{b}
SEM	34	28	24	0.22
CV%	2.72	2.88	3.00	1.52
Source of variation	--------------------- *P* values	---------------------		
Treatment	0.005	0.001	<0.001	0.027

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean; BW, body weight

[a,b] Means that do not share superscript letters in a column are significantly different ($P < 0.05$) by Tukey's test

Table 12. Effect of soybean sources on carcass and cut-up parts yield (grams) of Ross 708 male broilers at 47 days of age.

Treatment	**Whole carcass**	**Legs**	**Wings**	***Pectoralis major***	***Pectoralis minor***	**Rack+skin**
	------------------------	----------	------ g	------	----------	------------------------
NO-EE SB	2,933^{a}	885	269^{a}	953^{a}	191	632^{a}
NO-FF SB	2,811^{b}	868	262^{b}	884^{b}	186	609^{b}
NO-FF SB	2,768^{b}	850	256^{b}	870^{b}	185	610^{b}
SEM	26	11	5	19	5	9
CV%	2.98	6.06	5.16	6.67	7.63	7.22
Source of variation	------------------------	----------	------ *P-values*	------	----------	------------------------
Treatment	<0.001	0.077	<0.001	0.001	0.221	0.023

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

[a,b] Means that do not share superscript letters in a column are significantly different ($P < 0.05$) by Tukey's test

Table 13. Effect of soybean sources on carcass parts, fat and visceral organs (grams) of Ross 708 male broilers at 47 days of age.

Treatment	**Neck**	**Shanks**	**Fat**	**Liver**	**Pancreas**	**Intestine**	**Gizzard + Proventriculus**	**Spleen**	**Fat**
	----------	----------	----------	----------	g	----------	----------	----------	----------
NO-EE	142	127^{a}	35	59	6	109	62	5	21
NO-FF SB	139	125^{ab}	32	58	7	109	58	4	19
HO-FF SB	140	120^{b}	37	59	7	105	59	4	20
SEM	3	1	3	2	0	3	2	0	2
CV%	9.93	6.95	49.99	12.19	16.69	13.23	17.46	24.2	53.66
Source of variation	----------	----------	----------	----------	*P*-values	----------	----------	----------	----------
Treatment	0.783	0.008	0.521	0.951	0.268	0.61	0.469	0.686	0.703

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

[a-b] Means in a column not sharing a common superscript are significantly different ($P < 0.05$) by Student *t* or Tukey’s test.

Table 14. Effect of soybean sources on cooking weight on the meat of Ross 708 male broilers at 47 days of age.

Treatment	Weight before cook	Weight after cook	Cooking loss
	------------ g	------------	--- % ---
NO-EE SB	469^a	384^a	17.95
NO-FF SB	438^b	357^b	18.03
HO-FF SB	434^b	351^b	18.87
SEM	8	6	0.46
CV%	7.63	9.09	8.61
Source of variation	--------------------- *P*-values	---------------------	
Treatment	0.009	0.002	0.456

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

[a,b] Means that do not share superscript letters in a column are significantly different ($P < 0.05$) by Tukey's test

Table 15. Effect of soybean sources on the dripping loss of Ross 708 male broilers at 47 d of age.

Treatment	Breast weight	Weight drip loss	Drip loss
	------------- g	-------------	--- % ---
NO-EE SB	339	334	1.38
NO-FF SB	318	314	1.40
HO-FF SB	313	309	1.41
SEM	11	11	0.10
CV%	11.85	11.92	16.13
Source of variation	------------------- *P*-values	-----------------	
Treatment	0.213	0.213	0.912

Abbreviations: NO-EE SB, normal oleic extruded expeller soybean; NO-FF SB, normal oleic full-fat soybean; HO-FF SB, high oleic full-fat soybean

CHAPTER 3

Standardized ileal amino acid digestibility of high-oleic full-fat soybean in broilers

Abstract

High oleic oil soybeans can produce high-quality protein meals, and their fatty acid content can improve several metabolic processes in broilers. However, its amino acid (AA) digestibility has not been determined. The objective of this study was to determine the apparent ileal AA digestibility (AID) and standardized ileal AA digestibility (SID) of high oleic full-fat (HO-FF) soybean compared to normal oleic full-fat (NO-FF), normal oleic extruded expeller (NO-EE), and solvent extracted soybean meal (SE SBM) in broilers. The extruded soybeans (SB) were all processed under similar conditions, and particle size was uniformized by roller-milling to obtain a geometric mean of 915-950 μm. The HO-FF contained 38.18% crude protein (CP), and 18.21% fat, the NO-FF, 38.31% CP and 18.21% fat, the NO-EE 43.80% CP, and 8.99% fat, and the SE SBM 47.15% CP and 2.57% fat. A nitrogen-free basal diet (NFD) was fed to one treatment with ten chicks/cage to determine basal endogenous losses (BEL). Titanium dioxide was used as an inert marker to calculate AA digestibility. The test diets contained 57.5% of the basal NFD and 42.5% of each of the four SBM sources. In this experiment, using a completely randomized design, 272 Ross-708 male broilers were placed in 40 battery cages and assigned to five treatments, with eight replicates per treatment. A common starter diet was provided to all the chickens for 14 d. All chickens had similar ($P > 0.05$) body weight (BW), feed intake (FI), and feed conversion ratio (FCR) before offering the NFD and the four test diets. Experimental diets were provided as mash during nine days of adaptation. Chickens were euthanized with CO_2 at 24 d, and the ileal distal portion contents were collected, frozen, and freeze-dried. The BEL were similar to the values found within the literature. The AA AID of the HO-FF SB was similar ($P < 0.001$) to the NO-FF SB but lower than the observed in NO-EE SB and SE SBM for Lys, Met, Val, Leu, Ile, Arg, Asp, Ala, Glu, Gly, and Ser. However, the AID of Thr, Trp, and Cys of HO-FF was similar to the NO-EE but consistently lower than SE SBM. The SID in the HO-FF SB was 88.10, 87.60, 81.73, 82.02, 83.18, 82.05, 85.07, and 91.29% for Lys, Met, Thr, Val, Leu, Ile, Trp, and Arg, respectively. These SID for HO-FF were lower than SE SBM and NO-EE SB but slightly higher than NO-FF SB. The AA and CP digestibility reduced ($P < 0.001$) from SE SBM, NO-EE, HO-FF to NO-FF SB. Values of SID of all AA for SE and NO-EE SB were similar to those reported in the literature for high-protein and high-quality SBM. In conclusion, the SID of AA from HO-FF is similar to other full-fat soybeans (FFSB) and lower than NO-EE and SE SBM.

Keywords: Soybean meal, amino acids, digestibility, broilers, high oleic soybean meal

Introduction

Worldwide corn-soybean diets are the most common for broiler chickens. In broilers, most digestion and absorption of protein and amino acid (AA) happens before digesta goes into the hindgut (Pond *et al*., 1995). Hence, an important factor for precise feed formulation and sustainable usage of feed ingredients is understanding the digestibility of AA. Digestibility can be defined as the difference between the amount of feed ingested and the amount of excreta produced, and it is essential to determine the quality of ingested nutrients (Blok *et al*., 2017). Nutrient digestibility studies are also critical for a better assessment of how effectively nutrients are digested and absorbed in the mid-section of the gastrointestinal (GI) tract (Olojede *et al*., 2018). Bacteria present in the caeca and colon may ferment the nutrients which are not digested and absorbed in the small intestine. During protein fermentation in the hindgut, AA may be produced, which cannot be utilized by the host as a source of AA. So ileal digestible AA presents a better picture of AA that are available to the broiler than AA digested in the total digestive tract. Due to this reason, the digestibility of protein and AA at the ileal portion is a vital characteristic of the nutritional value of feed ingredients (Blok *et al*., 2017), and digestibility in terminal ileum is considered a better sign of protein and AA availability than fecal digestibility (Ravindran and Bryden, 1999; Kadim *et al*., 2002).

Ileal digestibility measures the difference between the ingested AA amount and AA amount, which are recovered from digesta in the distal ileum. It can be expressed as apparent ileal digestibility (AID) or standardized ileal digestibility (SID). In AID, basal endogenous losses (BEL) are not considered, while in SID, BEL is deducted from the AID values (Kadim *et al*., 2002). BEL are inevitable losses that are directly related to the metabolic functions of the animal and not dependent on the diet type (Cowieson *et al*., 2009). The BEL of CP and AA flow is not dependent on the composition of test feedstuff and is proportional to the dry matter (DM) intake

(Jansman *et al*., 2002). The relative importance of BEL increases as the crude protein (CP) content of the ingredient decreases (Lemme *et al*., 2004). To estimate ileal digestible contents in ingredients and balanced diets, Stein *et al*. (2005) suggested using SID, which is corrected for BEL. Conventionally, the BEL in chickens is calculated following starvation or consuming a protein-free diet (Sibbald, 1987). The term excreta is used in poultry more frequently as it consists of feces and urine. Microorganisms in the hindgut can affect the AA contents in excreta, and undigested AA can be metabolized by this microbiota which will lead to modification of excreta contents and errors in digestibility estimation (Kong and Adeola, 2014). It is recommended that ileal digestibility data should be produced using broiler chickens if values will be used in the feed formulation of broilers (Ravindran *et al*., 2017).

In the case of dietary proteins, digestibility calculation will be more accurate if calculated in terms of digestible AA rather than total AA (Dalibard & Paillard, 1995; Rostagno *et al*., 1995; Williams, 1995; Parsons, 1996; Honda *et al*., 2010). SID is commonly used in chickens to estimate the AA availability of feedstuffs (Kong and Adeola, 2014). Procedures have been established which allow the *in vivo* assessment of AA in chickens (Papadopoulos, 1985). These include sampling and evaluating ileal digesta from chickens (Kadim *et al*., 2002). The standard methods to collect ileal digesta are gently squeezing (Short *et al*., 1999; Bandegan *et al*., 2009; Poureslami *et al*., 2012) or flushing (Ravindran *et al*., 2004; Kluth *et al*., 2005; Adedokun *et al*., 2007). After that, samples can be oven-dried (OD) or freeze-dried (FD) before the start of chemical analysis. Due to the practical nature of the two methods, moisture loss may not be the same while using different drying methods (Jindal and Siebenmorgen, 1987). FD is more time-consuming and costly than OD (Hinnant and Kothmann, 1988). When excreta samples were OD at 65 ^{o}C, there was an average energy loss of almost 12% (Manoukas *et al*., 1964); however, there was average nitrogen (N) loss of 4.7% when samples were FD or OD at 60 ^{o}C (Shannon and Brown, 1969). In another study, there was no significant effect of FD or OD at 60 ^{o}C on true AA availability of excreta samples (Dale *et al*., 1985).

For estimation of ileal nutrient digestibility, generally, indigestibility or inert digestibility markers are used. Several authors have reported using an inert marker to determine the rate of nutrient disappearance in the GI tract, its calculations, and chemical analysis (Jagger *et al*., 1992; Short *et al*., 1996; Adeola, 2001; Myers *et al*., 2004). They should not affect the digestive process, absorb, or act like nutrients of study in the GI tract of chickens. Markers include acid-insoluble ash, chromium oxide, ferric oxide, and titanium oxide. Some markers may show higher ileal AA digestibility than others, and their effect on animal digestibility studies is indecisive (Olojede *et al*., 2018). For the ileal digestibility value of N and individual AA, a higher recovery rate was observed for titanium (Ti) than Chromium (Cr) (Jagger *et al*., 1992). Likewise, the apparent ileal digestibility of AA was higher when Ti was used as compared to Cr (Olukosi *et al*., 2012). The low recovery rate of Cr may be attributed to the lack of its uniform distribution in digesta across the GI tract (Oberleas *et al*., 1990; Sooncharernying and Edwards, 1993) and some analytical problems caused by the presence of phosphorus and other minerals (Peddie *et al*., 1982; Saha and Gilbreath, 1991; Yin *et al*., 2000).

In broilers, the SID of AA can be affected by feed ingredient-specific factors (Park *et al*., 2020). Factors like feedstuff, type of protein, crude fiber, and anti-nutritional factors are important in AA digestibility. Feed ingredients and animal categories may also interact (Huang *et al*., 2006). Several studies indicated that AA digestibility of SBM may be influenced by cultivation site, season, processing method, and antinutritional factor content such as trypsin inhibitor (TI), lectins, saponins, and oligosaccharides (Parsons, 1991; Frikha *et al*., 2012; Kim *et al*., 2012). Variation in published AA ileal digestibility values also results from differences in ileal digestibility assay methods. Some important steps in digestibility methods are formulation and mixing of assay diets, *ad libitum* feeding of chickens for a specific time, euthanasia method to be applied in chickens, ileal digesta collection, digesta processing, and assessment of ingredients, diets, and digesta. AA digestibility values can be affected by any change in these steps (Ravindran *et al*., 2017). Due to heat treatment, a loss in lysine has been observed in full-fat soybeans (FFSB) and different qualities of soybean meal (SBM) (Fontaine *et al*., 2007). The AID of AA in chickens can be affected by age (Johns *et al*., 1986; Huang *et al*., 2005) and species of poultry (Huang *et al*., 2006, 2007).

FFSB has a high protein and energy content and is an important ingredient in chicken diets (Ravindran *et al*., 2014). However, FFSB is used after the heat treatment because raw soybean (SB) has a higher concentration of TI (Waldroup, 1982). Protein digestibility and AA availability can be affected by a high level of protease inhibitors, especially TI (Jahanian and Rasouli, 2016). Heat is also applied to soybean meal (SBM) after oil extraction from FFSB to reduce the TI. This heat treatment may affect the AA digestibility resulting in different AA digestibility values of FFSB and SBM (Park *et al*., 2017). The extrusion method followed by expelling the oil is a common SB processing technique (Bandegan *et al*., 2010). This method generates a product with higher oil content than solvent-extracted soybean meal (SE SBM) (Webster *et al*., 2003; Opapeju *et al*., 2006) but less than FFSB. Various research groups have also reported differences in AA digestibility coefficients of animals fed on extruded-expeller soybean compared to SBM (Woodworth *et al*., 2001; Lawrence *et al*., 2003; Opapeju *et al*., 2006; Baker and Stein, 2009).

Varieties of soybeans (Kinney, 1996), sunflower, and peanuts with higher oleic fatty acid content have been developed to provide higher levels of this fatty acid and lower saturated fatty acids to improve its nutritional value (Rodríguez *et al*., 2005; Toomer *et al*., 2020). However, the AID and SID of these varieties have not been reported. Consequently, the objective of this study is to determine the AID and SID of the high oleic full-fat (HO-FF) soybeans compared to SE SBM, normal oleic extruded-expeller (NO-EE), and normal oleic full-fat (NO-FF) soybean in broilers.

Materials and Methods

All the procedures involving the broilers used in this experiment were approved by North Carolina State University Institutional Animal Care and Use Committee.

Diets

All soybean sources were analyzed for nutrient profile and anti-nutritional contents by NIR and wet chemistry (Table 1). Five replicates of each soybean source were utilized for NIRS values, and average value was used. FFSB had a higher TI level which may be due to different processing methods to produce it as compared to NO-EE and SE SBM. Soybean contains phytate, which can interfere with the absorption of other minerals. Phytase enzyme was added to diets to increase the availability of dietary phosphorus and minerals to chickens. Foreign materials from soybeans were removed by using the Eclipse 324 seed and grain cleaner (Seedburo, Equipment Company). All extruded products were processed under similar conditions. Extrusion was conducted in a commercial feed mill, Mule City Feeds (Benson, NC, USA), by a single screw dry extrusion (InstaPro 2000 R, Iowa, USA) to produce full-fat soybean. The whole soybeans were extruded at a die temperature of 155 ^{o}C. Extruded expeller soybeans were produced by an additional expelling process which was done after extrusion. During this process, extruded soybeans were mechanically pressed to extract the oil, and the resulting product had less oil than extruded soybeans. Particle size was uniformized by roller-mill (Model C128889, RMS, Sea, SD) to obtain a geometric mean of 915-950 μm. The 50:50 and 50:25 settings were used for FFSB and extruded expeller soybeans, respectively.

A starter diet (1 – 14 d) was crumbled and pelleted at 85 ^{o}C with a corn particle size of 700 to 800 μm (Table 2). Starter diet was formulated (Concept 5 formulation) to meet and/or exceed nutrient requirements for broilers (Ross-708). A nitrogen-free diet (NFD) was formulated using corn starch and dextrose sugar (Table 3). Additionally, Solkafloc was included as a source of fiber, and all test diets were balanced to meet Ross-708 broiler recommendations. Titanium dioxide was added at 5 g/kg as an inert marker in each diet. Four soybean products were included in the NFD. These products were SE SBM, NO-EE, NO-FF, and HO-FF. The test diets contained 57.5% of the basal NFD and 42.5% of each of the four SBM sources.

Chicken husbandry

A total of 272 Ross-708 broiler chicks were used in this experiment. Male chickens were individually weighed, tagged, and separated by feather sexing to reduce the data variation in this experiment. Chicks were allocated randomly in battery cages in a small poultry house. Brooder battery cages (88 x 32 x 24 cm^3) were electrically heated, and the room temperature was maintained at 32, 28, and 24 ^oC during weeks 1, 2, and 3, respectively, under a 23 h light and one h dark cycle. Mortality was recorded daily. Each treatment had eight replicate cages. The same starter diet (3,000 kcal/kg energy and 22% CP) was provided to all the chicks until 14 days. Experimental diets were provided during the next nine adaptation days. Feed and water were provided to the broilers unrestricted for the whole experimental period. Only the NFD had ten broilers per cage to collect enough ileal digesta sample to be analyzed, while all others had six broilers per cage. NFD was fed to determine basal endogenous losses. Chickens were euthanized with CO_2 at 24 d, and distal ileum contents were collected by flushing portions of the ileum with distilled water. The contents were frozen, stored at -20^{o}C, and freeze-dried for lab analysis.

Chemical analysis

Feed and ileal samples were ground finely using a coffee grinder and analyzed for DM, CP, AA, and titanium dioxide contents. DM of feed and ileal samples were evaluated by drying in a forced draft oven (NFTA Method 2.1.4, AOAC Official Method 935.29 & 945.15). Grounded feed and digesta samples were sent to the University of Missouri Experiment Station and Chemical Laboratories for AA analysis by high-performance liquid chromatography [Method 982.30 E (a, b, c), AOAC International, 2006]. Titanium dioxide concentration was measured in triplicate in feed samples while duplicates for ileal samples, using a UV spectrophotometer following methods described by Myers *et al*. (2004).

Digestibility calculations

Ileal endogenous AA losses in broilers fed with NFD were calculated as milligrams of AA flow per 1 kg of DM intake (DMI) basis using the following formula by Moughan *et al*. (1992)

Ileal AA losses (mg/kg of DMI =

[AA in ileal digesta, mg/kg x (diet titanium, mg/kg/ileal titanium, mg/kg)]

Apparent ileal AA digestibility, % =

[1 – (titanium in diet / titanium in ileal digesta) x (AA in digesta / AA in diet)]

Standard ileal AA digestibility, % =

Apparent digestibility, % + [(indigenous losses AA, g/kg of DMI) / (AA content of the raw material, g / kg of DM)] x 100

Statistical analysis

Data were analyzed in a completely randomized design using ANOVA, while mean separation was done using Tukey's or Student's t-test at the significance level of $P < 0.05$. Data were analyzed using JMP pro 15 software (SAS Institute, Inc., Cary, NC).

Results

The nutrient content of the four sources of soybean diets evaluated is presented in Table 3. Apparent ileal AA digestibility was obtained from the four diets containing the soybean sources, and BEL were obtained from the NFD to calculate SID. The BEL (g/kg/DMI) and co-efficient of apparent digestibility of dry matter (CADDM) were obtained and presented in Table 5. Leu and Glu contributed the highest values to BEL for indispensable and dispensable AA, respectively. BEL of Trp for indispensable AA and Cys for dispensable AA were recorded as the lowest. HO-

FF showed a higher CADDM than NO-FF but less than NO-EE and SE SBM, while SE SBM had the highest ($P < 0.001$) CADDM, followed by NO-EE.

For indispensable AA (Table 5), the AID of HO-FF was slightly higher ($P < 0.001$) than NO-FF in Arg, Lys, Thr, Trp, and Val; however, for Ile, Leu, and Met, it was less in HO-FF than NO-FF. Both HO-FF and NO-FF AA AID were lower ($P < 0.001$) than NO-EE and SE SBM. For all these AA, the highest AID ($P < 0.001$) was observed for the SE SBM. For dispensable AA, HO-FF showed more AID ($P < 0.001$) than NO-FF in Asp, Cys, and Glu, but NO-FF had slightly high AID values for Ala, Gly, and Ser. SE SBM and NO-EE had greater AID ($P < 0.001$) than NO-FF and HO-FF for dispensable AA, while NO-EE had lesser values than SE SBM. Also, HO-FF showed higher values ($P < 0.001$) than NO-FF for total AA (TAA) and CP but less than NO-EE and SE SBM.

Similar to AA AID, an interaction ($P < 0.001$) was observed for AA SID for indispensable and dispensable AA for all soybean sources (Table 6). Among indispensable AA, HO-FF had higher SID ($P < 0.001$) than NO-FF in Arg, Leu, Lys, Met, Thr, and Trp, while only for Ile and Val, NO-FF showed better SID than HO-FF. However, both soybean sources had lower ($P < 0.001$) SID than SE SBM and NO-EE for all indispensable AA, respectively. Between dispensable AA, HO-FF indicated higher SID ($P < 0.001$) values for Asp, Cys, and Glu while lower values for Ala, Gly, and Ser as compared to NO-FF. For all these dispensable AA, the highest SID ($P < 0.001$) were observed for SE SBM and NO-EE, respectively than HO-FF and NO-FF, while only Glu was the exception, for which NO-EE had more SID than SE SBM. For TAA and CP values, HO-FF was higher ($P < 0.001$) than NO-FF, but both were lower than NO-EE and SE SBM.

Discussion

Several studies have examined the ileal AA digestibility values of FFSB for broilers with well-specified processing conditions of soybeans. Still, available data on the ileal AA digestibility of HO-FFSB for broilers is minimal. Valencia *et al*. (2009) presented the AA SID data of FFSB, but they used the micronized FFSB instead of extruded SB. In this experiment, the AID and SID values for different soybean sources were higher than in studies conducted by Iyayi and Adeola (2014), Ravindran *et al*. (2014), and Park *et al*. (2017). As expected, the CP and AA concentration was lower in HO-FF and NO-FF than in NO-EE and SE SBM. Both full-fat soybean sources were extruded only and had more oil content. The concentration of these two nutrients was intermediate in NO-EE SB sources compared to FFSB and SE SBM. As suggested by previous studies, the TI activity (TIA) content was within the range of 2.74 to 5.70 TIU/mg for FF soybeans (Baker *et al*., 2010; Goebel and Stein, 2011; Ravindran *et al*., 2014; Woyengo *et al*., 2014). TIA value was least in the SE SBM and comparable in NO-EE with FFSB. Both FFSB sources have the same TIA value. The cause for different values of TIA may be variations in temperature during processing. Increased temperature and time during conditioning or expanding of FFSB can reduce the TIA, urease activity, and protein solubility (Heger *et al*., 2016). So, it is possible that heat processing of FFSB may not be sufficient to maximize its AA availability. The value of AID of some indispensable (Arg, Lys, Thr, Trp, Val) and dispensable AA (Asp, Cys, Glu) was higher in HO-FF than NO-FF, while few were higher in NO-FF than HO-FF, but both were close to each other.

BEL of indispensable and dispensable AA for broiler chickens observed in the current experiment were comparable to previous studies; however, dispensable AA was slightly lower in values (Kong and Adeola, 2013; Adedokun *et al*., 2014; Ravindran *et al*., 2014; Park *et al*., 2017). It should be considered that the BEL of AA may be altered by the ingredient composition of the NFD. Park *et al*. (2017) only used dextrose. However, in this experiment, NFD was made with cornstarch (78.08 %) and dextrose (6.50 %). The quantitative flow of basal endogenous AA at the terminal ileum depends on the methodology used for quantification of the age of the animals and the presence of phytate and phytase in the diet (Blok *et al*., 2017).

In a study conducted by Iyayi and Adeola (2014), AA SID of FFSB was calculated and compared with other ingredients (peanut flour, wheat bran, corn, sorghum, and fish meal) for broilers at 26 d. For the SID of indispensable AA of FFSB, the highest value was determined for Arg (84.9%) and the lowest for Thr (69.8%). Lys and Met showed SID values of 80.6 and 77.1%, respectively. While for the dispensable AA, Glu had the highest SID (84.3%) and Cys had the lowest (56.9%). Park *et al*. (2017) conducted a study and SID (%) of FFSB was compared with SE SBM (43 and 47% CP) in broilers at 26 d. AA SID of FFSB was lower ($P < 0.05$) than SE SBM (43%) and SE SBM (47%) for all the indispensable and dispensable AA. On average, FFSB had 9.49 and 10.50 % less AA SID values than SE SBM (43%) and SE SBM (47%). The average AA SID of four different FFSB samples ranged from 76.9% to 82.7% in broilers at 34 d, and these values are lower than SE SBM, which may be due to diluting effect of fat (Ravindran *et al*., 2014). In the current experiment, the SID of AA and CP in HO-FF was less than NO-EE and SE SBM; The higher TI content in FFSB sources (4.68% than 3.17 and 0.40% in NO-EE and SE SBM, respectively) may be a reason for it. However, despite the same TI content in both full-fat sources, some AA (Arg, Leu, Lys, Thr, Trp, Asp, Glu) and CP (%) were higher in HO-FF than NO-FF but very similar in values. In a study by Palliyeguru *et al*. (2011), broilers were fed on a corn SBM-based diet with 300 g/kg FFSB, and the AID of CP linearly decreased as TIA was increased from 3.61 to 16.1 TIU/mg. They concluded that a higher level of TIA in soybeans might be the main reason for low protein digestibility. However, in a study by Clarke and Wiseman (2005), a variation was observed in digestible AA content, although the TIA values in both samples were very similar (3.6 and 3.4 mg/g). This indicates that not only TIA, but other variables may impact the AA digestibility in FFSB. Valencia *et al*. (2009) also mentioned the lesser values of SID of CP, Leu, Met, Val, and Ala in the broiler, which were FFSB than those fed with SBM (452 g/kg CP); however, no differences were detected in the remaining AA between FFSB and SBM.

In the present study, experimental diets were given for nine days, and digesta samples were collected at 24 d of age, affecting the SID values. The differences among values in various studies may be due to variations in processing methods, various FFSB, or both. Heating time plays a significant role in the processing of FFSB. Weight gain and feed efficiency of broilers fed diets with 371.8 g/kg FFSB were quadratically increased when the autoclaving time of FFSB was increased from 0 to 90 mins at 121 ^{o}C; however, chickens fed with FFSB, which was autoclaved for more than 40 mins, had reduced BW and feed efficiency (Herkelman *et al*., 1991). So, these factors can lead to differences in AA digestibility. The gizzard is the main organ that regulates the passage of digesta to the intestine, and particle size can also influence nutrient digestibility. In the current study, the average particle size of all soybean sources was kept the same. Another well-known factor that impacts digestibility is fiber in the diet. But in the current study, fiber content (4 %) was kept the same for all the treatments. However, fat content was different among the treatments. HO-FF and NO-FF soybean treatment contain 7.83% fat than 5.11 and 5.13% fat of NO-EE and SE SBM. The higher fat content can be a reason for low AA digestibility due to the nutrient dilution effect (Ravindran *et al*., 2014).

Conclusion

Using FFSB instead of SBM reduced the AID of the total AA of HO-FF by 5.39 and 8.05% compared to NO-EE and SE SBM, respectively. The lowest AA AID of HO-FF was observed for Cys (dispensable AA) and the highest for Arg (indispensable AA). At the same time, the SID of the total AA of HO-FF was less by 3.94 and 6.26% than NO-EE and SE SBM, respectively. Values of AID and SID of AA and CP were similar for NO and HO-FF. SE SBM showed the highest AID and SID for AA and CP than all other SB sources. Low AID and SID of HO-FF than NO-EE and SE SBM is less desirable for nutritionists to consider it for use in broiler diets regarding protein digestibility.

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Table 1. Nutrient composition of soybean sources used in experiment.

Nutrient	**SE SBM**	**NO-EE SB**	**Full-fat soybean**	
			NO	**HO**
Protein, crude, %	47.15	43.80	38.31	38.18
Fat, crude, %	2.57	8.99	18.21	18.21
Fiber, crude, %	3.77	5.27	6.10	6.10
Calcium, %	0.34	0.20	0.28	0.28
Phos. total, %	0.63	0.57	0.48	0.48
Ash, %	6.83	6.41	5.52	5.52
Phos. available, %	0.23	0.19	0.16	0.16
Lysine, %	2.83	2.66	2.34	2.40
TSAA, %	0.64	1.21	1.06	1.13
Threonine, %	1.81	1.68	1.49	1.49
Valine, %	2.22	2.07	1.82	1.82
Leucine, %	3.52	3.33	2.86	2.80
Tryptophan, %	1.29	0.59	0.51	0.50
Trypsin inhibitor, mg/g	0.95	7.46	11.02	11.02
Dig. Lysine, %	2.57	2.36	2.03	2.09
Dig. Methionine, %	0.56	0.51	0.44	0.44
Dig. Cystine, %	0.55	0.49	0.40	0.45
Dig. TSAA, %	1.12	1.00	0.84	0.89
Dig. Threonine, %	1.52	1.41	1.24	1.24
Dig. Tryptophan, %	0.57	0.52	0.43	0.41
Dig. Isoleucine, %	1.93	1.82	1.51	1.49
Dig. Leucine, %	3.20	2.97	2.50	2.45
Dig. Valine, %	1.97	1.80	1.55	1.55
Dig. Histidine, %	1.08	0.99	0.87	0.88
Dig. Arginine, %	3.20	2.91	2.48	2.58
Dig. Phenylalanine, %	2.16	1.96	1.69	1.68
Palmitic acid C16:0, %	0.67	0.80	1.93	1.20
Palmitoleic acid C16, %	0.00	0.01	0.03	0.02
Stearic acid C18:0, %	0.17	0.26	0.61	0.48
Oleic acid C18:1, %	0.68	1.40	3.12	11.13
Linoleic acid C18:2, %	2.65	3.79	9.55	1.71
Linolenic acid C18:3, %	0.41	0.59	1.45	0.02

Abbreviations: TSAA, total sulfur amino acids; SE SBM, solvent extracted soybean meal; NO-EE SB, normal oleic extruded expeller soybean; NO, normal oleic; HO, high oleic

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

Table 2. Ingredient and nutrient composition of starter diet (1 – 14 d).

Ingredient %	Diet
Corn	50.94
Solvent extracted SBM	19.07
Extruded expeller SB	7.00
NO Full-fat SB	7.00
HO Full-fat SB	6.54
DDGS	3.75
Poultry fat	1.33
Limestone fine	1.39
Dicalcium phosphate	1.09
DL-Methionine	0.37
Sodium bicarbonate	0.27
L-Lysine	0.27
Salt, plain (NaCl)	0.28
Mineral premix[1]	0.20
Choline chloride 60	0.18
L-Threonine	0.16
Vitamin premix[2]	0.10
Coccidiostat[3]	0.05
Phytase[4]	0.02

Nutrient Name	Diet
M.E. Poultry, kcal/kg	3000
Protein, crude, %	22.83
Fat, crude, %	7.33
Fiber, crude, %	2.93
Calcium, %	0.94
Phos. total, %	0.56
Ash, %	5.56
Phos. available, %	0.34
Lysine, %	1.41
TSAA, %	1.05
Threonine, %	1.00
Valine, %	1.05
Leucine, %	1.90
Tryptophan, %	0.27
Trypsin inhibitor, mg/g	2.20
Dig. Lysine, %	1.28
Dig. Methionine, %	0.66
Dig. Cystine, %	0.29
Dig. TSAA, %	0.95
Dig. Threonine, %	0.86
Dig. Tryptophan, %	0.23
Dig. Isoleucine, %	0.86
Dig. Leucine, %	1.82
Dig. Valine, %	0.95
Dig. Histidine, %	0.50
Dig. Arginine, %	1.37
Dig. Phenylalanine, %	1.04
Palmitic acid C16:0, %	0.40
Palmitoleic acid C16, %	0.01
Stearic acid C18:0, %	0.12
Oleic acid C18:1, %	1.17
Linoleic acid C18:2, %	1.55
Linolenic acid C18:3, %	0.25

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

[1] Trace minerals provided per kg of premix: manganese (Mn SO4), 60 g; zinc (ZnSO4), 60 g; iron (FeSO4), 40 g; copper (CuSO4), 5 g; iodine (Ca(IO3)2),1.25 g.

[2] Vitamins provided per kg of premix: vitamin A, 13,227,513 IU; vitamin D3, 3,968,253 IU; vitamin E, 66,137 IU; vitamin B12, 39.6 mg; riboflavin, 13,227 mg; niacin, 110,229 mg; d-pantothenic acid, 22,045 mg; menadione, 3,968 mg; folic acid, 2,204 mg; vitamin B6, 7,936 mg; thiamine, 3,968 mg; biotin, 253.5 mg.

[3] Coban® 90 (Monensin), Elanco Animal Health, Greenfield, IN, at 500 g/ton.

[4] Natuphos E® (500 FTU/kg, 50 g/ton FTU).

Table 3. Ingredient and nutrient composition of experimental diets (15 – 23 d) used in experiment.

Diet	**NFD**	**Solvent extracted SBM**	**Extruded expeller**	**Full fat**	
				Normal oleic	**High oleic**
Ingredient (%)					
Corn starch	78.08	40.26	43.5	45.13	45.13
Dextrose sugar	6.50	6.50	6.50	6.50	6.50
Soybean oil	5.00	4.00	1.21		
Solka floc 40	3.00	1.36	1.42	1.06	1.06
Dicalcium phosphate	2.38	1.84	1.95	2.00	2.00
Limestone fine	0.95	0.86	0.96	0.84	0.84
Titanium dioxide	0.50	0.50	0.50	0.50	0.50
Salt	0.36	0.33	0.34	0.32	0.32
Sodium bicarbonate	0.05	0.14	0.10	0.10	0.10
Mineral premix[1]	0.20	0.20	0.20	0.20	0.20
Choline chloride	0.30	0.30	0.30	0.30	0.30
Vitamin premix[2]	0.10	0.10	0.10	0.10	0.10
Soybean meal solvent extracted		42.50			
Extruded expeller soybean			42.50		
Normal oleic full-fat soybean				42.50	
High oleic full-fat soybean					42.50
Potassium carbonate	1.33	0.05	0.06	0.05	0.05
Arbocel	1.00	1.00	0.30	0.30	0.30
Magnesium oxide 58%	0.26	0.06	0.08	0.09	0.09
	100	100	100	100	100
Nutrient					
M.E. Poultry, kcal/kg	3,638	3,136	3,153	3,360	3,360
Dry matter, %	90.63	90.39	91.96	92.07	92.07
Protein, crude, %	0.07	20.07	18.65	16.32	16.27
Fat, crude, %	5.11	5.13	5.11	7.83	7.83
Fiber, crude, %	4.08	4.00	4.00	4.00	4.00
Calcium, %	0.87	0.87	0.87	0.87	0.87
Phos. Available, %	0.44	0.44	0.44	0.44	0.44
Sodium, %	0.20	0.20	0.20	0.20	0.20
Potassium, %	0.76	0.93	0.76	0.76	0.76
Chloride, %	0.25	0.25	0.25	0.25	0.25
Trypsin inhibitor, mg/g		0.40	3.17	4.68	4.68
Dig. Lysine, %		1.09	1.00	0.86	0.89
Dig. Methionine, %		0.24	0.22	0.19	0.19
Dig. Cysteine, %		0.24	0.21	0.17	0.19
Dig. Total sulfur amino acids, %		0.47	0.43	0.36	0.38
Dig. Threonine, %		0.65	0.60	0.53	0.53
Dig. Tryptophan, %		0.24	0.22	0.18	0.18
Dig. Isoleucine, %		0.82	0.77	0.64	0.63
Dig. Leucine, %		1.36	1.26	1.06	1.04
Dig. Valine, %		0.84	0.77	0.66	0.66
Dig. Arginine, %		1.36	1.24	1.05	1.10
Dietary electrolytes, MEQ/kg	225	269	225	225	225
Palmitoleic acid C:16, %		0.00	0.00	0.01	0.01
Stearic acid C18:0, %		0.07	0.11	0.26	0.20
Oleic acid C18:1, %		0.29	0.60	1.33	4.73
Linoleic acid C18:2, %		1.13	1.61	4.06	0.73
Linolenic acid C18:3, %		0.17	0.25	0.62	0.21

Abbreviation: NFD, nitrogen free diet

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

[1] Trace minerals provided per kg of premix: manganese (Mn SO4), 60 g; zinc (ZnSO4), 60 g; iron (FeSO4), 40 g; copper (CuSO4), 5 g; iodine (Ca(IO3)2),1.25 g.

[2] Vitamins provided per kg of premix: vitamin A, 13,227,513 IU; vitamin D3, 3,968,253 IU; vitamin E, 66,137 IU; vitamin B12, 39.6 mg; riboflavin, 13,227 mg; niacin, 110,229 mg; d-pantothenic acid, 22,045 mg; menadione, 3,968 mg; folic acid, 2,204 mg; vitamin B6, 7,936 mg; thiamine, 3,968 mg; biotin, 253.5 mg.

Table 4. Live performance of Ross 708 male broilers in battery cages before and after starting the experimental period according to the assigned treatment.

Treatment	NFD	Solvent extracted SBM	Extruded expeller soybean	Full-fat soybean: Normal oleic	Full-fat soybean: High oleic	SEM ±	CV%	*P*-value: Treatment
0 - 14 d								
BW, g	497	483	477	489	505	7.80	4.30	0.108
BWG, g	454	439	433	445	461	7.72	4.68	0.098
Feed intake, g	515	499	501	499	514	7.26	3.93	0.297
FCR (g:g)	1.136	1.130	1.134	1.122	1.117	0.01	2.22	0.527
0 - 23 d								
BW, g	442^{c}	924^{a}	844^{b}	794^{b}	847^{b}	15.05	5.48	<0.001
BWG, g	398^{c}	879^{a}	800^{b}	750^{b}	803^{b}	15.02	5.80	<0.001
Feed intake, g	1,097^{b}	1,321^{a}	1,293^{a}	1,295^{a}	1,331^{a}	22.88	4.96	<0.001
FCR (g:g)	2.757^{a}	1.534^{d}	1.598^{cd}	1.726^{d}	1.660^{bc}	0.02	2.97	<0.001
14 - 23 d								
BWG, g	-59^{d}	421^{a}	353^{b}	296^{c}	330^{bc}	12.3	12.96	<0.001
Feed intake, g	582^{b}	825^{a}	792^{a}	795^{a}	817^{a}	18.4	6.82	<0.001
FCR (g:g)	-10.232^{b}	1.974^{a}	2.258^{a}	2.712^{a}	2.480^{a}	0.32	-566.80	<0.001

Abbreviations: BW, body weight; BWG, body weight gain; FCR, feed conversion ratio; NFD, nitrogen free diet; SBM, soybean meal

[a-d] Means in a column not sharing a common superscript are significantly different ($P < 0.001$) by Student *t* or Tukey's test.

Table 5. Apparent ileal amino acid digestibility and co-efficient of apparent digestibility of dry matter of different dietary treatments.

Soybean type	**Basal endogenous loses**	**Solvent extracted SBM**	**Extruded expeller soybean**	**Full fat soybean**		**SEM**	**CV %**	***P-value***
				Normal oleic	**High oleic**			
	g/kg DMI	---------------------------- % ----------------------------						
CADDM	-	48.81^{a}	40.48^{b}	36.65^{b}	40.37^{b}	1.37	9.15	<0.001
Indispensable amino acids								
Arg	0.27	92.34^{a}	91.64^{a}	88.24^{b}	89.16^{b}	0.56	1.74	<0.001
Ile	0.43	85.85^{a}	82.71^{b}	78.03^{c}	76.69^{c}	0.76	2.61	<0.001
Leu	0.56	86.03^{a}	83.60^{a}	79.19^{b}	78.88^{b}	0.71	0.05	<0.001
Lys	0.38	89.20^{a}	87.00^{b}	83.81^{c}	84.75^{c}	0.52	1.67	<0.001
Met	0.12	90.71^{a}	87.03^{b}	82.72^{c}	82.36^{c}	0.66	2.10	<0.001
Thr	0.46	82.65a	78.00^{b}	74.23^{c}	75.10^{bc}	0.89	3.25	<0.001
Trp	0.07	89.95^{a}	84.24^{b}	81.77^{b}	81.82^{b}	0.80	2.67	<0.001
Val	0.34	85.58^{a}	82.78^{a}	77.98^{b}	78.02^{b}	0.87	3.04	<0.001
Dispensable amino acids								
Ala,	0.37	85.95^{a}	83.48^{a}	79.71^{b}	78.54^{b}	0.67	2.23	<0.001
Asp	0.74	85.22^{a}	84.20^{a}	80.29^{b}	80.93^{b}	0.63	2.08	<0.001
Cys	0.23	77.32^{a}	69.41^{b}	63.27^{c}	66.47^{bc}	1.12	4.49	<0.001
Glu	0.79	89.61^{a}	89.37^{a}	86.27^{b}	86.87^{b}	0.48	1.50	<0.001
Gly	0.40	84.05^{a}	78.85^{b}	74.64^{c}	74.02^{c}	0.87	3.17	<0.001
Ser	0.45	85.52^{a}	81.15^{b}	76.40^{c}	75.71^{c}	0.80	2.74	<0.001
TAA	8.85	86.57^{a}	84.44^{a}	79.50^{b}	80.12^{b}	0.65	2.18	<0.001
CP	12.35	83.13^{a}	81.44^{a}	76.59^{b}	78.11^{b}	0.72	2.51	<0.001

Abbreviations: CADDM, co-efficient of apparent digestibility of dry matter; TAA, total amino acids; CP, crude protein, SBM, soybean meal

$^{a\text{-}c}$ Means in a column not sharing a common superscript are significantly different (*P < 0.001*) by Student *t* or Tukey's test

Table 6. Standard ileal amino acid digestibility of different dietary treatments.

Soybean type	**Solvent extracted SBM**	**Extruded expeller soybean**	**Full fat soybean**	
			Normal oleic	**High oleic**
	---------------------------- % --------------------------			
Indispensable amino acids				
Arg	94.16	93.67	90.60	91.29
Ile	89.87	87.41	82.68	82.05
Leu	89.36	87.42	82.94	83.18
Lys	91.93	90.66	87.45	88.10
Met	94.73	91.22	87.08	87.60
Thr	87.90	84.11	81.27	81.73
Trp	92.37	87.19	84.85	85.07
Val	88.76	86.42	82.14	82.02
Dispensable amino acids				
Ala	89.69	87.18	84.04	83.42
Asp	88.70	88.19	84.26	84.72
Cys	84.49	77.44	71.43	74.41
Glu	92.00	92.11	88.92	89.43
Gly	88.20	83.71	80.20	79.36
Ser	90.09	86.94	82.44	80.11
TAA	90.63	88.65	84.96	85.29
CP	89.03	87.37	84.03	84.95

Chapter 4

Nitrogen-corrected apparent metabolizable energy of high oleic full-fat soybean in broilers

Abstract

Soybeans from different processing methods are included in broiler diets. A new variety of soybeans with high-oleic fatty acid content is available and estimating its energy value for broilers is essential. In this study, we determined the apparent metabolizable energy (AME), apparent metabolizable energy corrected by the nitrogen (AMEn), digestibility, and nitrogen (N) retention of full-fat high oleic (HO-FF) soybean as compared to solvent-extracted soybean meal (SE SBM), normal oleic full-fat (NO-FF) and extruded expeller (NO-EE) soybean. A total of 240, Ross-708 male broiler chickens were used in a randomized design with eight replicate cages per treatment and six chicks placed in each cage. AMEn was calculated with basal energy diet (BD), and titanium dioxide was used as an inert marker. The same starter diet was provided for 14 days, and experimental diets were provided during the next five adaptation days. Excreta was collected for three successive days until 23 days after the adaptation days. Excreta of chickens were collected twice a day, and feathers were removed before freezing and storing. AME and AMEn were calculated by considering the digestibility marker and total excreta collection. In the first method, the coefficient of apparent digestibility of dry matter (CADDM) and crude protein (CP) digestibility were also calculated along with their relative values. In the partial collection method, AME and AMEn values of the HO-FF diet ($P < 0.001$) were 3,222 and 3,034 kcal/kg, respectively, which were higher than other sources but lower than NO-FF (3,228 and 3,048 kcal/kg). The SE showed 2,947 and 2,719 kcal/kg of AME and AMEn, while for NO-EE, it was 3,045 and 2,841 kcal/kg, respectively. The highest CADDM and CP digestibility values ($P < 0.001$) were obtained by chickens fed HO-FF (62.23 and 55.21%, respectively) compared to other treatments except for the BD, which had respective values of 65.32 and 61.41%. For the total excreta collection method, results were quite similar with AME and AMEn values ($P < 0.001$) of HO-FF (3,533 and 3,297 kcal/kg, respectively) better than others except for NO-FF, which had 3,551 and 3,316 kcal/kg. N retention for HO-FF ($P < 0.001$) was 64.43%, lower than NO-FF and BD. In contrast, the digestibility value ($P < 0.001$) was 68.95% which was only lower than the BD with 72.01%. In conclusion, HO-FF diet showed higher AME, AMEn, CADDM, and CP digestibility values than SE SBM and NO-EE diets but lower AME and AMEn than the NO-FF diet.

Keywords: Soybean meal, apparent metabolizable energy, apparent metabolizable energy corrected by nitrogen, broilers.

Introduction

In the broiler production system, feed contributes toward the major cost, and feed ingredients used to provide protein and energy make the most of this cost. When diets are formulated or balanced, energy is the first part to be considered. Dietary energy plays an essential role in feed consumption and is the main factor in broiler chicken growth (Abdollahi *et al*., 2021). Hence, it is crucial to accurately evaluate the available energy content in feedstuffs for broilers.

In broilers, available energy from feed ingredients is established using apparent metabolizable energy (AME) and nitrogen-corrected apparent metabolizable energy (AMEn) (Veluri and Olukosi, 2020). A precise finding of the AME value of feed ingredients is significant because these values are used in feed formulation leading to improved feed efficiency and decreased feed costs (Olukosi *et al*., 2017; Adeola *et al*., 2018).

Although the metabolizable energy (ME) system has been generally used since its introduction in the mid-1950s (Hill and Anderson, 1958), it is not a perfect energy evaluation system (Lopez and Leeson, 2007; Liu *et al*., 2017; Mateos *et al*., 2019; Wu *et al*., 2020; Abdollahi *et al*., 2021). ME can be affected by different factors, including animal species, breeds, age, and feed intake (Sibbald, 1975; Sibbald, 1976). Also, the ME system does not consider the efficacy of various nutrients and the quantity of heat generated. However, considerable variability in stated AME and AMEn values for different feed ingredients makes it challenging to utilize them in feed formulation and interpretation of values.

In the ME system, the difference between gross dietary energy (GE) consumed and the GE expelled in the excreta (feces and urine) is determined as available energy (Hill and Anderson, 1958; Khalil *et al*., 2021) and is indicated as AME. Excreta is very important when measuring the ME. It has dietary energy and non-dietary energy, while it comprises metabolic and urinary energy. There may be feces loss and energy gain or loss from cecal fermentation and microbial culture.

However, ME is generally accepted for defining the available energy in poultry ingredients. Reasons include the easy process and collection, no need for bird culling, and it accounts for most of the energy losses after digestion and metabolism.

For measuring the AME of feeds and ingredients for poultry, three primary methods are used, which are: direct, substitution, and regression methods. They are different in the preparation of assay diets, and each method has its advantages and disadvantages (Abdollahi *et al*., 2021). Excreta collection is a standard procedure in all methods and can be done as a total or partial method.

The direct method is most common due to its ease of assay diets and calculations. Only one ingredient is used as a single energy source in the test diet; this method is usually employed for cereal grains (Lockhart *et al*., 1967). On the downside, this technique is not suitable for poorly palatable ingredients. Additionally, if these diets are used longer, they will negatively impact physiological functions because cereals are not balanced nutritionally. So, these diets cannot be utilized for extended feeding days (Abdollahi *et al*., 2021). The difference or substitution method is another option to estimate the AMEn of ingredients. It can be applied to ingredients with low palatability, high protein content, or high level of anti-nutritional factors (ANFs). The critical factor is to prepare a reference or basal diet (BD) which is complete and nutritionally balanced. Ingredients to be tested are incorporated in BD at different levels to prepare the assay diets (Veluri and Olukosi, 2020). The level of BD substitution varies by ingredient (Sibbald and Slinger, 1963; Kong and Adeola, 2014). This is a good alternative to the direct method because the reference diet is standard. However, BD composition and precision of BD AME calculation can affect the AME of the test ingredient. While using this method, it is presumed that there is no interaction between BD and test ingredients (Sibbald *et al*., 1960), but this assumption is not always valid. Also, the AME value of a test ingredient can be affected by its inclusion level (Olukosi, 2021). The third method to determine the AME of ingredients is the regression method in which basal and test diets are used, but a minimum of two levels of ingredients are substituted in the BD. The appropriate inclusion level of ingredients is assessed to the energy value of individual diets to predict the AME of the test ingredient (Kong and Adeola, 2016).

The AME values of ingredients or diets are generally corrected for nitrogen (N) retention (AMEn), so all the data can be converted to N equilibrium for comparison. The effect of differential growth rate inherited across chickens in any assay can be accommodated by correction for N retention, especially in growing broilers (Lopez and Leeson, 2008). In contrast to corn, the ME of ingredients such as soybean meal (SBM) is supposed to be significantly affected by correction for N retention (Dale and Fuller, 1984) due to more protein content. N correction permits strain comparison and adjusts any age-associated effects; however, a cross-strain comparison is less significant as broiler nutrition is now very specialized, but within poultry, age and strain may be influential (Mollah *et al*., 1983; Hätel, 1986; Bourdillon *et al*., 1990; Carré *et al*., 1995; Farrell *et al*., 1997; Lopez and Leeson, 2008). On the other hand, N correction is not a biological norm, particularly for modern-day broilers with large feed intakes, rapid growth, and the associated accumulation of protein and fat. The N correction effect is also employed to reduce the variability of ME estimates of ingredients that have variations in protein content (Leeson *et al*., 1977).

SBM is frequently used in poultry feed due to its high protein content, ideal amino acid (AA) profile, and digestibility (Ravindran *et al*., 2014). In the past, studies have been done to determine or compare the AA digestibility and ME values of SBMs prepared using different processing techniques, varieties, origins, genotypes, etc. (Parsons *et al*., 2000; de Coca-Sinova *et al*., 2008; Pacheco *et al*., 2013).

A variety of soybeans with high oleic fatty acid was developed to improve the positive impact of high oleic fatty acid in meat which is ultimately considered suitable for human consumption (Slaughter *et al*., 2019). But no data is available regarding the energy values of high oleic full-fat (HO-FF) soybeans. Thus, the objective of this experiment is to evaluate the AME and AMEn of HO-FF soybeans and their comparison with other soybean sources, including solvent-extracted soybean meal (SE SBM), normal oleic extruded expeller (NO-EE), and normal oleic full-fat (NO-FF) soybean, so that it can be used in feed formulation for broilers.

Materials and Methods

North Carolina State University Institutional Animal Care and Use Committee approved all the procedures involving the broilers used in this experiment.

Feed ingredients evaluated

Four soybean products were included in the basal diet. These products were SE SBM, NO-EE, NO-FF, and HO-FF soybeans. All soybean sources were analyzed for nutrient profile and anti-nutritional contents by near-infrared spectroscopy (NIRS) and wet chemistry

Diets

All soybean sources were analyzed for nutrient profile and anti-nutritional contents by NIR and wet chemistry. Five replicates of each soybean source were utilized for NIRS values and average value was used. Full-fat soybean had a higher trypsin inhibitor level which may be due to different processing method to produce it as compared to NO-EE and SE SBM. Nutrient composition of soybean sources is shown in Table 1. A starter diet (1 – 14 d) was formulated (Concept 5 formulation) to meet and/or exceed nutrient requirements for broilers (Ross-708). Diet formulation was based on digestible AA, mixed with SE SBM and corn ground to 700 to 800 µm pelleted at 85 ^{o}C, and crumbled (Table 2). Later, a basal / reference diet was formulated using corn and SE SBM (Table 3).

Additionally, all test diets were balanced for minerals and vitamins level to meet Ross-708 broiler recommendations. Phytate in soybean can restrict the mineral bioavailability, so phytase enzyme was added to diets to increase the overall availability of dietary phosphorus to chickens. Titanium dioxide was added at 5 g/kg as an inert marker in each diet. The test diets contained 70% of the BD and 30% of the four soybean sources.

Foreign materials from soybeans were removed by using the Eclipse 324 seed and grain cleaner (Seedburo, Equipment Company). All extruded products were processed under similar conditions. Extrusion was done in a commercial feed mill, Mule City Feeds (Benson, NC, USA), by a single screw dry extrusion (InstaPro 2000 R, Iowa, USA) to produce full-fat soybean (FFSB). The whole soybeans were extruded at a die temperature of 155 ^{o}C. While to produce extruded expeller soybean, an additional step of the expelling process was carried out after extrusion. The FFSB was mechanically pressed during this process to extract oil from them. All extruded products were processed under similar conditions, and particle size was uniformized by roller-mill (Model C128889, RMS, Sea, SD) to obtain a geometric mean of 915-950 μm to match the same particle size observed in the SE-SBM. The 50:50 setting was used for HO-FF and NO-FF, while 50:25 was used for extruded expeller soybeans.

Chicken husbandry

A total of 240 Ross-708 broiler chicks were used in this experiment. Chickens were feather-sexed, weighed, and tagged. Chicks were allocated randomly in the battery. Brooder battery cages (88 x 32 x 24 cm^3) were electrically heated, and the room temperature was maintained at 32, 28, and 24 ^{o}C during weeks first, second, and third, respectively, under a 23 h light and one h dark cycle. Mortality was recorded daily. Each treatment had eight replicate cages with six broilers per cage. The same starter diet (3,000 kcal/kg energy and 22% crude protein, CP) was provided to all the chicks until fourteen days. Experimental diets were provided during the next five adaptation days. The BD was fed to one treatment. Feed and water were provided to the broilers unrestricted for the experimental period.

Sample collection

The excreta were collected after the adaptation days of test diets for continuous three days until twenty-three days. Excreta were collected twice daily, and feathers or feed particles were removed immediately. Excreta were mixed and pooled by cage before storing and freezing at -20 ^{o}C in sterilized and labeled plastic bags.

Chemical analysis

Feed and excreta samples were ground finely using a coffee grinder and analyzed for dry matter (DM), CP only for feed, N, calories, and titanium dioxide contents. DM of feed and excreta samples were evaluated by drying in a forced draft oven (NFTA Method 2.1.4, AOAC Official Method 935.29 & 945.15). Grounded feed and excreta samples were analyzed for N by Fisons NA2000 Carbon Nitrogen Analyzer (AOAC 968.06-1969) and calorie content by Parr Model 6200. Titanium dioxide concentration was measured in triplicate in feed and excreta samples using an ultraviolet spectrophotometer following methods described by Myers *et al*. (2004).

Calculations

The AMEn values were determined for every dietary treatment as per the following equation (Kong and Adeola, 2014):

$$\text{AMEn (kcal/kg)} = \text{GEi} - [\text{GEo} \text{ X } (\text{Ni} / \text{No})] - 8.22 \text{ X } \{\text{Ni} - [\text{No} \text{ X } \text{Ni} / \text{No}]\}$$

Where GEi and GEo are gross energy values (kcal/kg) in diet and excreta; Ni and No are N values (g/kg DM) in diet (intake) and excreta (output). N correction factor of 8,220 kcal/kg (8.22) of retained N was used to calculate MEn. It is based on the energy estimation needed when 1 kg of tissue N is catabolized (Hill and Anderson, 1958).

Statistical Analysis

Data were analyzed in a completely randomized design using ANOVA, while mean separation was done using Tukey's or Student's t-test at the significance level of $P < 0.05$. Data were analyzed using JMP pro 15 software (SAS Institute, Inc., Cary, NC).

Results

Broilers were raised to 23 d and weighed on 14, 19, and 23 d (Table 4). As expected, no significant ($P > 0.05$) difference among chickens assigned to the different treatments, but fed the same diet, was observed at 14 d. Broilers fed on HO-FF had better body weight and body weight gain ($P < 0.05$) at 19 d than other treatments except for BD. NO-FF, followed by HO-FF showed a better feed conversion ratio (FCR) ($P < 0.05$) than other treatments at 19 d. At 23 d, no significant effect was observed on body weight and body weight gain. HO-FF had better FCR ($P < 0.001$) than other treatments except for NO-FF. Broiler fed on HO-FF consumed more feed than NO-FF and NO-EE but lower than those fed on BD and SE SBM.

AME (kcal/kg) values were analyzed using two methods (partial and total collection) and are shown in Table 6. On average, the partial collection method had 2.05% lower AME and AMEn values than the total collection method. For the first method (partial collection), the coefficient of apparent digestibility of dry matter (CADDM) and CP digestibility (%) were also determined, along with their relative values. The AME and AMEn values ($P < 0.001$) of HO-FF diet were higher than NO-EE diet and SE SBM diet, but it was less than NO-FF diet. The AME and AMEn values of HO-FF and NO-FF were very close, but these values were 8.54 and 10.38% higher for HO-FF than SE SBM. Although the highest AME and AMEn were observed in NO-FF, the highest CADDM and CP digestibility ($P < 0.001$) were calculated for HO-FF. The SE SBM had the lowest CADDM and CP digestibility (%). The NO-EE soybean had higher CADDM and CP digestibility (%) than SE SBM but lower than FF SBMs. In this method, AME and AMEn values of test ingredients on a DM basis were the same in order, and HO-FF soybean had better AME and AMEn than NO-EE and SE SBM but lower than NO-FF soybean. HO-FF soybean has 25.47% more AME and AMEn than commonly used SE SBM.

The AME and AMEn calculated with the total collection method were higher for all feed ingredients evaluated than the partial collection method. Digestibility (%) and N retention (%) in the total collection method were calculated for the basal and test diets. Similar results were observed with this method, HO-FF diet had less AME and AMEn ($P < 0.001$) than NO-FF but was higher than all other treatments. The AME and AMEn were very close to each other, while the lowest values ($P < 0.001$) were recorded for SE SBM. AME and AMEn for HO-FF were 9.09 and 9.16% higher than SE SBM and 6.71 and 7.22% higher than NO-EE, respectively. Other than the BD, the highest digestibility (%) was recorded ($P < 0.001$) for HO-FF among the four test diets, while the lowest value was recorded for SE SBM. The digestibility (%) of NO-FF was quite close to HO-FF, while NO-EE was near SE SBM. The N-retention (%) of HO-FF was less ($P < 0.001$) than NO-FF, and the highest value was calculated for the BD. N retention (%) of NO-EE and SE SBM were less than HO-FF. On a DM basis, the HO-FF had the highest AME and AMEn value. HO-FF soybean had almost 39% more AME and AMEn than SE SBM in both methods (Table 7).

Discussion

The ME system is a primary energy utilization model employed to define chickens' requirements and diet formulation. Efforts have been made to improve the precision of ME estimation for many kinds of ingredients accessible, and this system has been used extensively to compare energy values of feed ingredients or diets (Lopez and Leeson, 2008). ME is a function of diet and animal, so there can be variability of ME values influenced by different factors. These factors include methodology (Farrell *et al*., 1991), age of the chicken (Lessire *et al*., 1982; Sibbald, 1982), and species and strain (Leeson, 1974; Spratt and Leeson, 1987; Bourdillon *et al*., 1990). The effects of soybean sources on broiler growth performance were not the primary goal of this experiment, but this information is valuable to point out that diets were palatable and supported the standard growth performance of broilers.

In a study conducted by Dourado *et al*. (2010), no difference was observed between the total and partial collection methods for energy determination of SBM. However, in that experiment, acid insoluble ash (AIA) was used as a digestibility marker. In the current experiment, titanium dioxide was used, and AME and AMEn values were higher in the total collection method. No interaction was analyzed for soybeans between the two methods. However, as discussed with Dr. Olayiwola Adeola (Purdue University, West Lafayette, IN) the ratio between partial and total collection method values should be 0.95 or more, which was true for this study. For example, in partial and total collection methods, the AME of HO-FF was 3,847 and 3,992 kcal/kg (DM basis). The ratio between these values (3,847 / 3,922) corresponds to 0.98 which is larger than 0.95. The total excreta collection method depends on calculating total feed intake and excreta for a specific period and it is generally used to determine ME for broiler feed (Sakomura and Rostagno, 2007). The contamination of excreta with feed particles, feathers or intestinal mucosa sloughing can affect results and may limit the usage of this method (Dourado *et al*., 2010). In partial excreta collection method, ME is calculated by proportion of indigestible substance (marker) present in feed and excreta and this technique is characterized by use of marker (Dourado *et al*., 2010). A most significant factor to be concerned about when testing digestibility with markers is its recovery rate in the excreta. This recovery rate can be changed by different factors, for example, the marker amount included in the diets. In the gastrointestinal tract, high silica levels (more than 2%) in diets can affect the feed passage rate, which can affect digestibility (Cheng and Coon, 1990). AIA level can affect the AME values in oats when using enzymes (Scott and Boldaji, 1997). Hence, nutrient estimation can be affected by diet composition with the usage of markers. Feed passage rate may be affected by the contents of some components such as fiber and, ultimately, marker recovery rate (Dourado *et al*., 2010).

Titanium dioxide is a normally used inert marker in broiler diets. Inert markers should have the same digestive transit speed as other dietary nutrients, be physiologically inactive, indigestible, non-toxic, easy to analyze, and homogenously mixed into the diet (Jagger *et al*., 1992; Titgemeyer *et al*., 2001). It is a white color powder that is almost odorless and tasteless. It is not soluble in water and hydrochloric acid (Peddie *et al*., 1982). Tiny amounts of titanium dioxide can be used in diets without side effects and its quantitative recovery is possible from excreta (Askew, 1931; Njaa, 1961). Titanium dioxide is preferred over the commonly used chromium oxide due to better reproducibility and homogeneity (Jagger *et al*., 1992). It can also be used as an approved feed additive by the Food and Drug Administration, which is not the case for Chromium oxide (Titgemeyer *et al*., 2001). AIA is also a commonly used marker, but its digestive transit passage rate does not accurately match the passage of feed rate (Cheng and Coon, 1990).

In this experiment, two sources of FFSB, normal and high oleic, were processed under similar extrusion conditions. Nearly identical values of AME and AMEn of full-fat soybeans in both collection methods may result from the same processing procedure and lack of enough nutritional differences between these two sources. Good quality control of FFSB for proper ingredient utilization is evident in it. However, high oleic soybeans were different than normal oleic soybeans in the fatty acid profile, but other nutrient contents were almost the same.

In young broilers, the metabolizability of SBM is also linked with the increased viscosity of this ingredient on intestinal digesta (Mahagna *et al*., 1988). The ingredient digestibility will be decreased additionally if the enzymatic system is underdeveloped. The digestive system of the broiler behaves the same as FFSB even if the fatty acid content of oleic acid is different, which was the case in our current study.

AMEn value of FFSB was reported to be near 3,228 kcal/kg by Ravindran *et al*. (2014), and almost the same values were reported by Dalólio *et al*. (2016). In our current study, both FFSB varieties have nearly similar energy values, but the energy values of soybean samples were higher (on average) than reported values in the literature (Table 5). Variations in data between different FFSBs can occur due to different factors resulting in different values. It can occur due to processing type, type of cultivar used, planting type, and place of origin (Valencia *et al*., 2009). Even for similar soybean processing methods, there is no complete standardization of conditions of temperature, humidity, time, and pressure (Freitas *et al*., 2005).

The experimental time frame may affect the energy values. If the oil is replaced at a high level and excreta collection time is increased, these factors can negatively affect digestion and absorption of fats, giving non-practical energy values (Bertechini *et al*., 2019). For comparative purposes, ingredients, and diets ME values are usually corrected for N retention to transform all data to a base of N equilibrium. N retention changes with the age of the bird, bird type, and probably strain; hence, a correction factor is essential to compare ME values for the same ingredient (Leeson *et al*., 1977). A difference was noted between energy values with and without correction of retained N. It can signify the value of considering the use of N compounds which can be retained and excreted as uric acid (Liu *et al*., 2017). In the current study, a difference in ME and MEn values of different test ingredients can be attributed to N retention, as the CP level was different in test diets.

AME can be affected by the type of BD. A study conducted by Lopez and Leeson (2008) demonstrated that when SBM was replaced by 10, 20, and 30% of the total BD, AME values for SBM were calculated as 2,478, 2,568, or 2,352 kcal/kg on a DM basis for broilers with age from

9 to 12 d. For the same substitution level of SBM, AME was calculated as 2,353, 2,468, or 2,572 kcal/kg on a DM basis for broilers from 30 to 33 d. In the current study, average AME values for SBM were 349 kcal/kg higher than this study when calculated for the chickens with a 30% inclusion level at the age of 23 d. Age of broilers, and diet composition may be contributed to the energy difference. The maximum inclusion level of test ingredients is generally based on nutrient balance and palatability. A variability among ME values can be occurred by a low inclusion level of test ingredients (Mateos and Sell, 1980), but high inclusion level of test ingredients can also cause nutritional imbalances depending on the nutritional composition of the ingredient (Sibbald and Slinger, 1962).

In a study conducted by Perryman and Dozier (2012), the AMEn value of two SE SBM was calculated as 2,073 and 2,241 kcal/kg in growing broilers (Table 5). These two samples were taken in different years but from the same geographical location. In another study by Lopez and Leeson (2008), the AMEn value of SE SBM was reported from 2,170 to 2,383 kcal/kg for broilers with different inclusion levels. The AME and AMEn of NO-EE soybeans were higher than SE SBM in the current study but less than NO-FF and HO-FF soybeans. NO-EE soybeans have less amount of inherent oil than FFSB but more amount of oil than SE SBM, and it leads to higher values of ME. In poultry diets, NO-EE soybean is considered an excellent alternative source of ME but available data regarding ME values of NO-EE soybeans for broilers are scarce (Powell *et al.*, 2011).

Moreover, oligosaccharides (OS) in SBM, such as raffinose and stachyose, are somehow accountable for the decline in energy digestibility seen when considering SBM for chickens (Leeson and Summers, 2001). The nutritive value of SBM oligosaccharides remains uncertain in broiler feeds (Kocher *et al.*, 2003). A study conducted by Leske *et al.* (1991 and 1993) mentioned that an increase was noted in the true metabolizable energy of SBM when ethanol extraction was used to remove the OS. Contrarily, no beneficial effect was seen on SBM's nutritive value when depolymerized OS was done by adding α-galactosidase (Irish *et a*l., 1995). SBM has almost 6% soluble non-starch polysaccharides (NSP) and 18 to 21% insoluble NSP, while corn has nearly 0.9% soluble NSP and 6% insoluble NSP (Bach Knudsen, 1997).

Lopez and Leeson (2008) stated that the AMEn values of SE SBM were 7 to 12 % less than AME when calculated using a corn-soybean diet. A 10, 15, and 19% decline was reported in ME values of peanut flour meal, cottonseed meal, and canola meal, respectively, in broilers when adjusted for N correction (Zhang and Adeola, 2017). In the current study, a decrease of 6.30 to 8.35 % and 6.72 to 9.38 % were noticed in AME values of test ingredients on a DM basis in partial and total collection methods, respectively, after N correction.

The literature shows a need to conduct further investigation on FFSB regarding energy values. The energy values can be changed due to the method applied to determine them and the processing method and conditions used to obtain FFSB. To the best of our knowledge, this is the first data available related to energy utilization for HO-FF soybeans in broilers.

Conclusion

HO-FF soybean is a valuable ingredient that can be used in place of NO-EE and SE SBM. HO-FF has similar AME and AMEn values to the NO-FF soybean but 39 and 24% higher than SE SBM and NO-EE soybean, respectively, when the partial collection method was used. However, AME values for HO-FF soybean were higher by 37, and 25%, and AMEn values were higher by 40 and 29% than SE SBM and NO-EE soybean, respectively, during the total collection method.

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Table 1. Nutrient composition of soybean sources used in experiment.

Nutrient	SE SBM	NO-EE SB	Full-fat soybean	
			NO	HO
Protein, crude, %	47.15	43.80	38.31	38.18
Fat, crude, %	2.57	8.99	18.21	18.21
Fiber, crude, %	3.77	5.27	6.10	6.10
Calcium, %	0.34	0.20	0.28	0.28
Phos. total, %	0.63	0.57	0.48	0.48
Ash, %	6.83	6.41	5.52	5.52
Phos. available, %	0.23	0.19	0.16	0.16
Lysine, %	2.83	2.66	2.34	2.40
TSAA, %	0.64	1.21	1.06	1.13
Threonine, %	1.81	1.68	1.49	1.49
Valine, %	2.22	2.07	1.82	1.82
Leucine, %	3.52	3.33	2.86	2.80
Tryptophan, %	1.29	0.59	0.51	0.50
Trypsin inhibitor, mg/g	0.95	7.46	11.02	11.02
Dig. Lysine, %	2.57	2.36	2.03	2.09
Dig. Methionine, %	0.56	0.51	0.44	0.44
Dig. Cystine, %	0.55	0.49	0.40	0.45
Dig. TSAA, %	1.12	1.00	0.84	0.89
Dig. Threonine, %	1.52	1.41	1.24	1.24
Dig. Tryptophan, %	0.57	0.52	0.43	0.41
Dig. Isoleucine, %	1.93	1.82	1.51	1.49
Dig. Leucine, %	3.20	2.97	2.50	2.45
Dig. Valine, %	1.97	1.80	1.55	1.55
Dig. Histidine, %	1.08	0.99	0.87	0.88
Dig. Arginine, %	3.20	2.91	2.48	2.58
Dig. Phenylalanine, %	2.16	1.96	1.69	1.68
Palmitic acid C16:0, %	0.67	0.80	1.93	1.20
Palmitoleic acid C16, %	0.00	0.01	0.03	0.02
Stearic acid C18:0, %	0.17	0.26	0.61	0.48
Oleic acid C18:1, %	0.68	1.40	3.12	11.13
Linoleic acid C18:2, %	2.65	3.79	9.55	1.71
Linolenic acid C18:3, %	0.41	0.59	1.45	0.02

Abbreviations: TSAA, total sulfur amino acids; SE SBM, solvent extracted soybean meal; NO-EE SB, normal oleic extruded expeller soybean; NO, normal oleic; HO, high oleic

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

Table 2. Ingredient and nutrient composition of starter diet (1 – 14 d).

Ingredient %	Diet
Corn	50.94
Solvent extracted SBM	19.07
Extruded expeller SB	7.00
NO Full-fat SB	7.00
HO Full-fat SB	6.54
DDGS	3.75
Poultry fat	1.33
Limestone fine	1.39
Dicalcium phosphate	1.09
DL-Methionine	0.37
Sodium bicarbonate	0.27
L-Lysine	0.27
Salt, plain (NaCl)	0.28
Mineral premix[1]	0.20
Choline chloride 60	0.18
L-Threonine	0.16
Vitamin premix[2]	0.10
Coccidiostat[3]	0.05
Phytase[4]	0.02

Nutrient Name	Diet
M.E. Poultry, kcal/kg	3000
Protein, crude, %	22.83
Fat, crude, %	7.33
Fiber, crude, %	2.93
Calcium, %	0.94
Phos. total, %	0.56
Ash, %	5.56
Phos. available, %	0.34
Lysine, %	1.41
TSAA, %	1.05
Threonine, %	1.00
Valine, %	1.05
Leucine, %	1.90
Tryptophan, %	0.27
Trypsin inhibitor, mg/g	2.20
Dig. Lysine, %	1.28
Dig. Methionine, %	0.66
Dig. Cystine, %	0.29
Dig. TSAA, %	0.95
Dig. Threonine, %	0.86
Dig. Tryptophan, %	0.23
Dig. Isoleucine, %	0.86
Dig. Leucine, %	1.82
Dig. Valine, %	0.95
Dig. Histidine, %	0.50
Dig. Arginine, %	1.37
Dig. Phenylalanine, %	1.04
Palmitic acid C16:0, %	0.40
Palmitoleic acid C16, %	0.01
Stearic acid C18:0, %	0.12
Oleic acid C18:1, %	1.17
Linoleic acid C18:2, %	1.55
Linolenic acid C18:3, %	0.25

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

[1] Trace minerals provided per kg of premix: manganese (Mn SO4), 60 g; zinc (ZnSO4), 60 g; iron (FeSO4), 40 g; copper (CuSO4), 5 g; iodine (Ca(IO3)2),1.25 g.

[2] Vitamins provided per kg of premix: vitamin A, 13,227,513 IU; vitamin D3, 3,968,253 IU; vitamin E, 66,137 IU; vitamin B12, 39.6 mg; riboflavin, 13,227 mg; niacin, 110,229 mg; d-pantothenic acid, 22,045 mg; menadione, 3,968 mg; folic acid, 2,204 mg; vitamin B6, 7,936 mg; thiamine, 3,968 mg; biotin, 253.5 mg.

[3] Coban® 90 (Monensin), Elanco Animal Health, Greenfield, IN, at 500 g/ton.

[4] Natuphos E® (500 FTU/kg, 50 g/ton FTU).

Table 3. Ingredient and nutrient composition of the experimental diets (15 – 23 d) used in experiment.

Diet	Basal Energy	Solvent extracted SBM	Extruded expeller	Full fat	
				Normal oleic	High oleic
Ingredient (%)					
Corn	62.05				
Soybean oil	2.29				
Limestone fine	1.06				
Dicalcium phosphate	0.98				
Titanium dioxide	0.50				
DL-Methionine	0.31				
Salt, plain (NaCl)	0.30				
Sodium bicarbonate	0.25				
Mineral premix[1]	0.20				
L-Lysine	0.20				
Choline chloride	0.18				
L-Threonine	0.10				
Vitamin premix[2]	0.10				
Coban	0.05				
Quantum Blue	0.02				
Soybean meal solvent extracted	31.43	30			
Soybean meal extruded expeller			30		
Soybean meal full fat-normal oleic				30	
Soybean meal full fat-high oleic					30
Basal energy		70	70	70	70
	100	100	100	100	100
Nutrient					
M.E. Poultry, (kcal/kg)	3,000	2,820	2,920	3,098	3,098
Dry matter, %	88.55	88.82	90.11	90.29	90.29
Protein, crude, %	20.39	28.41	27.41	25.76	25.72
Fat, crude, %	5.91	4.91	6.84	9.6	9.6
Fiber, crude, %	2.14	2.63	3.08	3.33	3.33
Calcium, %	0.87	0.71	0.67	0.69	0.69
Phos. Available, %	0.44	0.37	0.36	0.35	0.35
Sodium, %	0.2	0.15	0.15	0.16	0.16
Potassium, %	0.91	1.27	1.15	1.15	1.15

Table 3 (continued).

Chloride, %	0.27	0.2	0.2	0.2	0.2
Trypsin inhibitor, mg/g	0.31	0.5	2.45	3.52	3.52
Dig. Lysine, %	1.09	1.53	1.47	1.37	1.39
Dig. Methionine, %	0.58	0.57	0.55	0.53	0.53
Dig. Cysteine, %	0.27	0.35	0.33	0.31	0.32
Dig. Total sulfur amino acids, %	0.84	0.92	0.89	0.84	0.86
Dig. Threonine, %	0.73	0.97	0.93	0.88	0.88
Dig. Tryptophan, %	0.21	0.32	0.31	0.28	0.27
Dig. Isoleucine, %	0.78	1.12	1.09	1	0.99
Dig. Leucine, %	1.59	2.08	2.01	1.87	1.85
Dig. Valine, %	0.84	1.18	1.13	1.05	1.05
Dig. Arginine, %	1.24	1.83	1.74	1.61	1.64
Dietary electrolytes, ME/kg	259	333	305	305	305
Palmitoleic acid C:16, %	0.00	0.00	0.00	0.01	0.01
Stearic acid C18:0, %	0.05	0.06	0.09	0.19	0.15
Oleic acid C18:1, %	0.22	0.26	0.48	1.00	3.40
Linoleic acid C18:2, %	0.85	0.94	1.29	3.01	0.66
Linolenic acid C18:3, %	0.13	0.14	0.20	0.46	0.17

The proximate composition was performed by an AOAC-certified lab, ATC Scientific (Little Rock, AR, USA)

[1] Trace minerals provided per kg of premix: manganese (Mn SO4), 60 g; zinc (ZnSO4), 60 g; iron (FeSO4), 40 g; copper (CuSO4), 5 g; iodine (Ca(IO3)2),1.25 g.

[2] Vitamins provided per kg of premix: vitamin A, 13,227,513 IU; vitamin D3, 3,968,253 IU; vitamin E, 66,137 IU; vitamin B12, 39.6 mg; riboflavin, 13,227 mg; niacin, 110,229 mg; d-pantothenic acid, 22,045 mg; menadione, 3,968 mg; folic acid, 2,204 mg; vitamin B6, 7,936 mg; thiamine, 3,968 mg; biotin, 253.5 mg.

Table 4. Live performance of Ross 708 male broilers in battery cages before and after starting the experimental period according to the assigned treatment.

Treatment	**Basal energy diet**	**Solvent extracted SBM**	**Extruded expeller soybean**	**Full-fat soybean**		**SEM ±**	**CV%**	***P* - value**
				Normal oleic	**High oleic**			**Treatment**
0 - 14 d								
BW, g	481	489	475	473	480	7.27	4.29	0.582
BWG, g	438	446	440	430	437	6.41	4.08	0.523
Feed intake, g	501	511	499	488	511	7.69	4.22	0.242
FCR (g:g)	1.163	1.161	1.158	1.155	1.170	0.01	2.21	0.820
0 - 19 d								
BW, g	804^{a}	770^{ab}	744^{b}	762^{ab}	772^{ab}	10.64	3.80	0.007
BWG, g	760^{a}	726^{ab}	701^{b}	719^{ab}	728^{ab}	10.66	4.03	0.007
Feed intake, g	927^{a}	902^{ab}	870^{b}	878^{ab}	893^{ab}	12.51	3.91	0.024
FCR (g:g)	1.219^{ab}	1.260^{a}	1.242^{ab}	1.194^{b}	1.213^{ab}	0.01	2.71	0.005
0 - 23 d								
BW, g	1,016	992	965	969	1,014	18.28	5.22	0.163
BWG, g	973	949	936	925	971	17.56	5.15	0.246
Feed intake, g	1,264^{a}	1,236^{ab}	1,155^{c}	1,177^{bc}	1,206^{abc}	19.02	4.54	0.002
FCR (g:g)	1.300^{a}	1.303^{a}	1.279^{ab}	1.245^{b}	1.255^{b}	0.01	2.18	<0.001
14 - 19 d								
BWG, g	320^{a}	281^{b}	270^{b}	291^{b}	292^{b}	6.74	6.56	<0.001
Feed intake, g	425^{a}	397^{ab}	371^{b}	383^{b}	382^{b}	7.18	5.18	<0.001
FCR (g:g)	1.332^{bc}	1.419^{a}	1.376^{ab}	1.281^{c}	1.311^{bc}	0.02	3.93	<0.001
14 - 23 d								
BWG, g	532	503	490	507	526	10.56	5.76	0.045
Feed intake, g	763^{a}	718^{ab}	676^{b}	681^{b}	696^{b}	12.13	4.78	<0.001
FCR (g:g)	1.429^{a}	1.429^{a}	1.385^{ab}	1.345^{bc}	1.312^{c}	0.02	3.30	<0.001

$^{a-c}$ Means in a column not sharing a common superscript are significantly different ($P < 0.05$) by Student *t* or Tukey's test.

Table 5. Summary of metabolizable energy (ME) values of various types of soybean meal (SBM) fed to poultry.*

Reference	**Method^1**	**Bird type**	**Ingredient^2**	**Estimate**	**Value^3 (kcal/kg DM)**
Coon *et al*. (1990)	Direct	Roosters	SE-SBM	TME$_n$	2,794
	Direct	Roosters	EE-SBM	TME$_n$	3,368
Zhang *et al*. (1993)	Direct	Roosters	EE-SBM	TME$_n$	3,125
	Direct	Roosters	EE-SBM	TME$_n$	3,265
	Direct	Roosters	EE-SBM	TME$_n$	3,239
Sulistiyanto *et al*. (1999)	Indirect	Broilers	SE-SBM	TME$_n$	2,150
	Indirect	Broilers	SE-SBM	TME$_n$	2,540
	Indirect	Broilers	SE-SBM	TME$_n$	2,451
Edwards *et al*. (2000)	Direct	Roosters	SE-SBM	TME$_n$	2,172
	Direct	Roosters	SE-SBM	TME$_n$	2,213
Parsons *et al*. (2000)	Direct	Roosters	SE-SBM	TME$_n$	2,739
	Direct	Roosters	SBM-LO	TME$_n$	2,931
Lopez and Leeson (2008)	Indirect	Broilers	SE-SBM	AME$_n$	1,962
	Indirect	Broilers	SE-SBM	AME$_n$	1,986
	Indirect	Broilers	SE-SBM	AME$_n$	1,998
	Indirect	Broilers	SE-SBM	AME$_n$	2,037
	Indirect	Broilers	SE-SBM	AME$_n$	2,286
	Indirect	Broilers	SE-SBM	AME$_n$	2,477
	Indirect	Broilers	SE-SBM	AME$_n$	2,170
	Indirect	Broilers	SE-SBM	AME$_n$	2,171
	Indirect	Broilers	SE-SBM	AME$_n$	2,180
	Indirect	Broilers	SE-SBM	AME$_n$	2,186
	Indirect	Broilers	SE-SBM	AME$_n$	2,327
	Indirect	Broilers	SE-SBM	AME$_n$	2,383
Baker *et al*. (2011)	Direct	Roosters	SBM-LO	TME$_n$	2,984
	Direct	Roosters	SE-SBM	TME$_n$	2,963
Perryman and Dozier (2012)	Indirect	Broilers	SE-SBM	AME$_n$	2,073
	Indirect	Broilers	SE-SBM	AME$_n$	2,241
	Indirect	Broilers	SBM-LO	AME$_n$	2,214
	Indirect	Broilers	SBM-LO	AME$_n$	2,435
	Indirect	Broilers	SBM-UL	AME$_n$	2,080
Loeffler *et al*. (2013)	Direct	Roosters	SE-SBM	TME$_n$	3,740
	Indirect	Broilers	SE-SBM	AME$_n$	3,468
Ravindran *et al*. (2014)	Indirect	Broilers	FF-SBM	AME$_n$	2,800
	Indirect	Broilers	FF-SBM	AME$_n$	3,357
	Indirect	Broilers	FF-SBM	AME$_n$	3,366
	Indirect	Broilers	FF-SBM	AME$_n$	3,395

*West, 2018.

[1] Direct – based on the test ingredient fed as the sole source, Indirect – based on the test ingredient fed as part of a complete diet.

[2] SE-SBM – solvent-extracted soybean meal, EE-SBM – expeller-extruded soybean meal, FF-SBM – full-fat soybean meal, SBM-LO – low oligosaccharide soybean meal, SBM-UL – ultra-low oligosaccharide soybean meal.

[3] Average ingredient estimates by bird type are as follows in kcal/kg DM: Broiler SE-SBM AME$_n$, 2,263; Broiler FF-SBM AME$_n$, 3,230; Broiler SBM-LO AME$_n$, 2,325; Broiler SE- SBM TME, 2,380; Rooster SE-SBM TME$_n$, 2,770; Rooster EE-SBM TME$_n$, 3,249; Rooster SBM-LO TME$_n$, 2,958.

Table 6. Dry matter and crude protein digestibility, nitrogen correction, apparent metabolizable energy, and apparent metabolizable energy corrected by nitrogen of the experimental diets calculated by partial and total collection method.

Soybean Type	**Partial collection**				**Total collection**			
	AME	**AMEn**	**CADDM**	**CP digestibility**	**AME**	**AMEn**	**Digestibility**	**Nitrogen retention**
	---- kcal/kg ----			---- % ----	---- kcal/kg ----		--------- % ----------	
Basal energy diet (BD)	3,065^{b}	2,949^{ab}	65.32^{a}	61.41^{a}	3,367^{b}	3,158^{b}	72.01^{a}	69.90^{a}
BD + SBM solvent extracted	2,947^{b}	2,719^{c}	59.32^{b}	49.12^{c}	3,212^{c}	2,995^{c}	65.67^{c}	56.65^{d}
BD + SBM extruded expeller	3,045^{b}	2,841^{b}	60.45^{b}	53.83^{b}	3,296^{bc}	3,059^{c}	65.81^{c}	61.58^{c}
BD + Full fat SBM normal oleic	3,228^{a}	3,048^{a}	61.31^{b}	53.88^{b}	3,551^{a}	3,316^{a}	68.67^{b}	64.72^{b}
BD + Full fat SBM high oleic	3,222^{a}	3,034^{a}	62.23^{ab}	55.21^{b}	3,533^{a}	3,297^{a}	68.95^{b}	64.43^{bc}
SEM	31	31	0.83	1.03	23	21	0.64	0.82
CV%	4.76	4.99	6.62	9.18	2.14	2.07	3.00	4.15
Source of variation	-- ***P - values*** --							
Soybean type	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001

Abbreviations: AME, apparent metabolizable energy; AMEn, apparent metabolizable energy corrected by nitrogen; CADDM, co-efficient of apparent digestibility of dry matter; CP, crude protein

$^{a\text{-}c}$ Means in a column not sharing a common superscript are significantly different (*P < 0.001*) by Student *t* or Tukey's test.

Table 7. Apparent metabolizable energy (AME), and apparent metabolizable energy corrected by nitrogen (AMEn) of the ingredients calculated by partial and total collection methods on dry matter (DM) basis and standardized to 88% DM.

Soybean Type	**Partial collection**				**Total collection**			
	DM		**Standardized to 88% DM**		**DM**		**Standardized to 88% DM**	
	AME	**AMEn**	**AME**	**AMEn**	**AME**	**AMEn**	**AME**	**AMEn**
	---kcal/kg---							
Solvent extracted SBM	2,770^{b}	2,575^{c}	2,438^{b}	2,266^{c}	2,853^{c}	2,614^{c}	2,511^{c}	2,300^{c}
NO extruded expeller soybean	3,090^{b}	2,831^{b}	2,719^{b}	2,491^{b}	3,129^{bc}	2,835^{c}	2,754^{bc}	2,495^{c}
Normal oleic full-fat soybean	3,763^{a}	3,526^{a}	3,311^{a}	3,103^{a}	3,899^{a}	3,637^{a}	3,431^{a}	3,201^{a}
High oleic full-fat soybean	3,847^{a}	3,572^{a}	3,385^{a}	3,143^{a}	3,922^{a}	3,650^{a}	3,451^{a}	3,212^{a}

Abbreviations: AME, apparent metabolizable energy; AMEn, apparent metabolizable energy corrected by nitrogen; DM, dry matter

General conclusions

High oleic full-fat (HO-FF) soybean is an important ingredient, and due to its beneficial effect on meat's fatty acid profile, it can be used to enrich broiler meat. It has a rich profile of oleic acid, which can be used to manipulate broilers' fatty acid profile and positively impact human health. High oleic soybean oil has less trans-fatty acids and can potentially reduce the low-density lipoprotein, which is bad for human health. However, including HO-FF soybean in broiler diets requires proper processing. Under-processing will result in a high proportion of anti-nutritional factors, and over-processing may decrease amino acid availability. Full-fat soybean usage in commercial broiler diets is on the high side due to its blend of protein and oil at the same time. Broilers fed on HO-FF had less body weight and feed conversion ratio than broilers fed on normal oleic extruded expeller (NO-EE) and normal oleic full-fat (NO-FF) soybean. Still, it may be due to high trypsin inhibitor content in full-fat soybean source. However, no treatment effect was observed on the cut-up parts, visceral organs, and myopathies (woody breast and white striping). Only wooden breast (score 1) was affected by dietary treatment, and HO-FF tends to have lower myopathy. Apparent ileal digestibility (AID) and standardized ileal digestibility (SID) of HO-FF soybean in broilers were nearly similar to NO-FF. However, the AID of HO-FF was reduced by 5.39 and 8.05% compared to NO-EE and SE SBM, while the SID of HO-FF was less by 3.94 and 6.26% than NO-EE and SE SBM, respectively. Trypsin inhibitors (TI) present in soybeans can interfere with digestibility, and their inclusion level can vary due to processing techniques. The TI level for HO-FF soybean was 4.68 % which is within the normal range, but still, it was higher than TI level of SE SBM (0.40%) and NO-EE soybean (3.17%).

Other factors can also influence the full-fat soybean (FFSB) digestibility and are not limited to diluting effect of fat in FFSB, processing methods adopted to make FFSB, variety, heating time in FFSB processing, particle size and fiber content in the diet, etc. For energy values, HO-FF had the highest apparent metabolizable energy (AME) and AME corrected by nitrogen (AMEn) than other soybean sources. AME and AMEn values were nearly the same for HO-FF and NO-FF. In the partial method, HO-FF had 39 and 24 % higher AME and AMEn than SE SBM and NO-EE soybeans. For the total collection method, HO-FF soybean had 37 and 25% more AME values and 40 and 29% more AMEn values than SE SBM and NO-EE soybeans, respectively. In general, HO-FF soybeans can be used in broiler diets due to their protein and high energy content. Broilers fed on HO-FF soybean had improved meat quality with reduced saturated fat content and high oleic fatty acid content, which can positively affect soybean producers. Limited data is available regarding high oleic soybeans in chickens' diets, and more research is needed to investigate further.