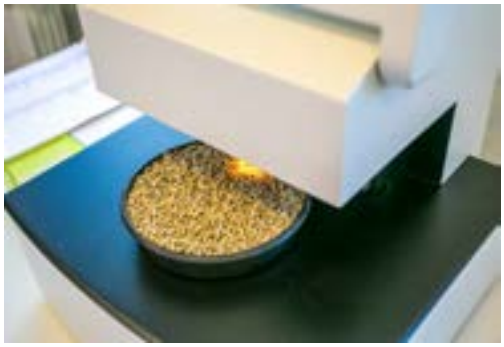
Manufacturing **Quality Feeds** with U.S. Crude Degummed **Soybean Oil:** Advantages, Benefits and Applications



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MANUFACTURING QUALITY FEEDS WITH U.S. CRUDE DEGUMMED SOYBEAN OIL: ADVANTAGES, BENEFITS AND APPLICATIONS

USSEC
U.S. SOYBEAN EXPORT COUNCIL

16305 Swingley Ridge Road
Suite 200
Chesterfield, MO 63017-USA
phone: 636.449.6400
fax: 636.449.1293
www.ussec.org

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DEAREST FRIENDS

I would like to extend my utmost gratitude for your interest in US Soybean Export Council (USSEC) programs. At USSEC, we strive to provide world class business solutions for our clients to grow and thrive. Your success is our success.

USSEC recruits and retains the best subject matter experts in the world to provide bleeding edge research, curated nutritional portfolios and sophisticated consultancy practices. It is in this vein that we are proud to bring you the US soybean oil handbook. Dr. Gerald (Jerry) Shurson is the world's foremost leader in lipid oxidation and soybean oil's nutritional characteristics. We are proud and honored to have Dr. Shurson on the team to provide this report.

Soybean meal derived from US soybeans has clear nutritional advantages, in terms of amino acid profile, metabolizable energy, and other essential nutrients. Now, we are proud to report that soybean oil derived from US soybeans also has unique nutritional benefits to compliment your rations.

While nobody can predict the future, if there is one thing that the coronavirus crisis taught us all it is that you must manage risk. Risk comes at you in myriad forms, but one way to buffer you from supply chain risk is to be open to a multitude of ingredients. This handbook is intended to be a comprehensive and useful resource for the nutritional assessment of US soybean oil.

At USSEC, we hope you think of us as investors in your business and stand at the ready to provide optimal solutions for whatever you may need. Should you have any questions or comments, we are always happy to assist.

I hope you find this report useful and experiment with adopting some of the measures prescribed herein.

Very best regards

KEVIN ROEPKE
REGIONAL DIRECTOR—THE AMERICAS
US SOYBEAN EXPORT COUNCIL

PREFACE

U.S. degummed soybean oil is a high value energy source for use in swine and poultry diets to improve caloric efficiency of pork, chicken, and egg production. It is produced in large quantities of consistent quality, which make it a preferred supplemental lipid source by nutritionists around the world.

U.S. degummed soybean oil also provides many additional benefits not found in other feed fats and oils. It is unique in that it is the only lipid source that contains high concentrations of both dietary essential fatty acids – linoleic and linolenic acid. It improves diet palatability and significantly reduces dust levels in feed mills and commercial confinement swine and poultry facilities. U.S. soybean oil has also been shown to reduce the adverse effects of heat stress on swine and poultry performance, as well as potentially minimizing the reduction in growth performance of broilers when consuming aflatoxin contaminated diets. Feed diets containing soybean oil to growing-finishing pigs has been shown to increase omega-6 fatty acids in pork, which is considered a healthier form of fatty acids for humans compared with saturated fatty acids. Similar effects occur in fatty acid composition of eggs from laying hens fed soybean oil.

U.S. soybean oil is the most widely research lipid source in animal feeds compared with any other fat or oil. Therefore, there is a vast amount of information available in the scientific literature that has been summarized in this U.S. Soybean Oil Handbook which should be used to optimize the nutritional and economic value of U.S. soybean oil in swine, broiler, and layer diets.

This Handbook was written by Dr. Gerald (Jerry) Shurson, Professor of Animal Nutrition in the Department of Animal Science at the University of Minnesota. Professor Shurson is world renowned for his team's research on assessing the nutritional value of feed fats and oils for swine and poultry, as well as the effects of lipid oxidation on animal health and performance. We greatly appreciated and acknowledge the co-authorship and invaluable contributions provided by Mr. Jeremiah Lechman, Director of Nutrition – Swine and Poultry, J & R Livestock Consultants, Ltd., Winnipeg, MB, Canada, in writing Chapter 6 of this Handbook, and for developing the U.S. Crude Soybean Oil Quality Assurance Guide and Checklist in the Appendix of Chapter 7.

Chapter

01

Overview of U.S. Soybean Oil Production

INTRODUCTION

Soybeans are grown in many countries around the world, and serve as an excellent source of oil and protein for human and animal consumption. The United States is the leading producer of soybeans globally, with about 36% of total soybean production worldwide. Production of U.S. soybeans have been steadily increasing during the past 20 years due to increasing demand for soybean meal for use as a high quality protein source in animal feeds. However, the increase in U.S. soybean production has also led to an increase in soybean oil production for use in human foods and animal feed, with over 11 million tonnes of soybean oil produced in 2018 (USDA, 2019).

Similarly, global production of vegetable oils has increased dramatically during the past 20 years. Palm oil is the predominant oil produced worldwide, and represents about 35% of total production, followed by soybean oil (26%), rapeseed or canola oil (15%), and sunflower oil (9%; Kerr et al., 2015). The remaining 15% of global vegetable oil production includes palm kernel oil, cottonseed oil, peanut oil, coconut oil, olive oil, and corn oil (Kerr et al., 2015). In addition, the oilseed industry also produces lecithin, soapstock, acid oils, and fatty acid distillates which are also used directly or through further processing and blending with other lipids in animal feeds (Kerr et al., 2015). In addition, by-products from the food industry such as restaurant grease, dried fats, mono- and diglycerides, and emulsifiers are also used as energy sources in animal feeds but to a lesser extent than vegetable oils. The production and use of animal fats for use in animal feeds has also increased over time, but less than for vegetable oils. Common animal fats used in the feed industry include edible and inedible tallow (about 57% of U.S. rendered fats), yellow grease (19%), lard and choice white grease (12%), and poultry fat (10%; Kerr et al., 2015). Lastly, animal fats are often blended with vegetable oils to produce various animal-vegetable blends that are also used as energy source in livestock and poultry feeds.

Of all of the possible lipid sources that can be used in swine and poultry diets, soybean oil is the most widely used and extensively research lipid source in swine and poultry diets around the world. Although U.S. soybean oil is produced primarily for human consumption, large quantities of crude, degummed soybean oil is produced for use in swine and poultry feeds in the domestic and export market. Canada and Latin America represent 61% of total U.S. soybean oil exports (USSEC Market Snapshots, 2018). U.S. soybean oil has become a preferred lipid source for use in swine and poultry diets because it is produced in large quantities annually to ensure a consistent, abundant supply. U.S. soybean oil also contains more metabolizable energy for swine and poultry than other commonly used lipid sources and its quality and composition is more consistent than most other feed fats and oils in the market. This is extremely important because nutritionists rely on consistent and predictable quality and nutritional value of feed ingredients in precision diet formulations to minimize risk of overfeeding or underfeeding energy in animal diets and capture the greatest economic value.

PRODUCTION OF U.S. SOYBEAN OIL

Soybeans are both nutritionally and economically important oilseeds because they contain a high amount of protein (48%) and oil (21%). Soybean processing results in the production of about 5.0 kg of crude oil, 20.1 kg of soybean meal, and about 1.5 kg of soybean hulls from each bushel (27.2 kg) processed (Hammond, 2005). Soybean oil can be extracted by using either mechanical or solvent extraction processes. Mechanical oil extraction involves the use of expellers, which are continuous screw-presses that are electrically powered. In contrast, solvent extraction is the most common method used to produce

soybean oil in the U.S., representing over 98% of soybeans processed (Hammond et al., 2005). However, solvent extraction it requires more capital investment and larger scale facilities than expellers. Typically, soybean solvent extraction facilities are capable of processing 2,500 to 5,000 tonnes of soybeans per day. Therefore, it is important to understand the solvent extraction process in the production of U.S. crude, degummed soybean oil for use in swine and poultry feeds.

SOYBEAN HARVEST AND STORAGE

U.S. soybean farmers harvest soybeans when the moisture content of about 13% is usually achieved by natural drying in the fields before harvesting. Achieving this moisture content is important for two reasons: 1) lower moisture can lead to soybeans splitting during handling and 2) higher moisture can cause mold growth or heat damage. In either case, preventing these types of damage is important to achieve a high grade and price, as well as optimize the amount and quality of oil from processing. Soybeans are typically stored in metal bins or concrete silos on farms or local elevators until delivery to the soy crushing facility.

CLEANING, PRE-CONDITIONING, AND CRACKING

Once soybeans are delivered from the farm to the soy crushing facility, they undergo a cleaning process to remove foreign material (e.g. stems, pods, broken seeds, dirt, and stones) by using shaker screens and aspirators **(Figure 1).**). Next, the soybeans are pre-conditioned by heating and drying to a moisture content of about 9.5% (Hammond et al., 2005). This improves the efficiency of hull removal, which is accomplished by cracking the seeds into smaller pieces with a corrugated roller mill, followed by aspiration of the hulls from the rest of the seed ("meat"). Fortunately, soybean hulls are relatively easy to remove compared to other oilseeds. Soybean hulls are removed because they contain less than 1% oil, increase the protein and reduce the fiber content of soybean meal, and reduce the volume of material undergoing further processing to reduce cost and improve efficiency of oil extraction. Aspirated hulls may be passed through gravity tables that further separate any remaining small particles of "meat".

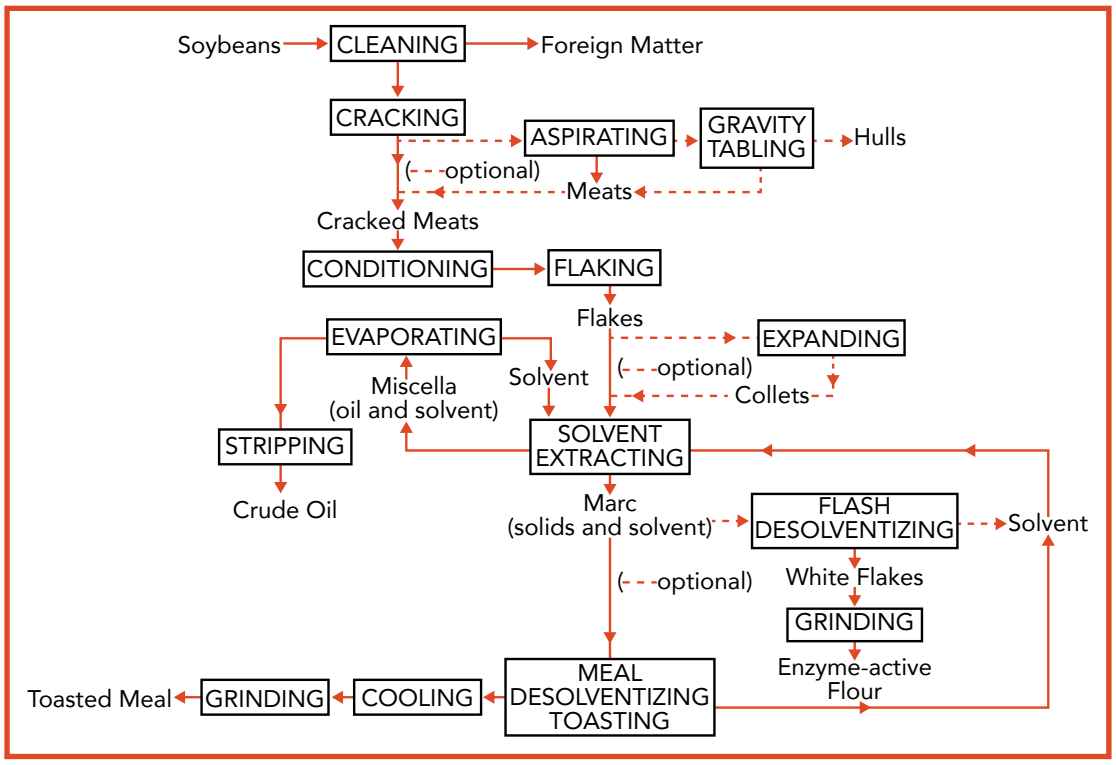

Figure 1. *Soybean oil solvent extraction process (Hammond et al., 2005)*

CONDITIONING, FLAKING, EXPANSION, AND SOLVENT EXTRACTION

Cleaned and dehulled soybeans are subsequently conditioned by heating to 74°C to soften the seed before flaking (0.25 mm) through smooth roller mills (**Figure 1;** Hammond et al., 2005). It is important to achieve proper cracking and conditioning because this causes the desired cell rupture for efficient oil extraction and minimize the amount of fine particles that interfere with optimal flaking and oil extraction (Hammond et al., 2005). The goal is to produce highly distorted membranes surrounding oil in cells and cell walls so that the oil can be easily extracted. Alternatively, use of expanders increases cell distortion and produces more dense pellets (collets) to allow easier oil extraction than from flakes (Hammond et al., 2005). The extent of use of expanders to process flakes vary among soy processing facilities ranging from one-third to all flakes being expanded, and may improve oil quality by inactivating phospholipases which cause phospholipids to not be hydratable (Hammond et al., 2005).

Flakes or collets are then conveyed to various types of extraction equipment (chain, basket, shallow-bed, deep-bed), where the solvent is continuously passed countercurrent to the transport of solids for 30 to 45 minutes in six or more stages (Hammond et al., 2005). Extraction occurs by percolation rather than immersion by allowing the solvent to flow by gravity through the extraction equipment. The solvent is comprised of a mixture of hexane isomers (45% to 70% n-hexane) obtained from petroleum distillate, and has a boiling temperature in the range of 65°C to 71°C. The highest quality oil, which is low in non-triacylglycerol components is extracted first, and as extraction continues, lower quality oil containing increasing concentrations of phosphatides, free fatty acids, and pigments is produced (Hammond et al., 2005). Most soybean processors extract as much oil as possible so that only 0.5% to 1.25% residual oil remains in the meal after the extraction process is complete (Hammond et al., 2005).

EVAPORATION, SOLVENT RECOVERY, AND STRIPPING

The oil-rich extract (miscella), containing 20 to 30% oil, is transferred to solvent recovery equipment (Figure 1; Hammond et al., 2005). Solvent recovery consists of two-stage evaporators and an oil stripper. After exiting the first-stage evaporator, the oil content is increased to about 65% to 70% oil, and after heating with vapors from the desolventized toaster and going through the second-stage evaporator, the oil concentration is increased to 90% to 95% (Hammond et al., 2005). Steam-injection vapor, high temperature and vacuum are used in the oil stripper to remove the solvent to a concentration of less than 0.2% in the soybean oil (Hammnod et al., 2005). The temperature in the oil stripper should not exceed 115°C to prevent burning the oil and causing a dark color (Hammond et al., 2005). All of the evaporated solvent is recycled back to the extractor, and oil is transferred to a vacuum dryer to remove any residual steam condensate from the stripper (Hammond et al., 2005). The crude soybean oil is then cooled and moved to storage. A high proportion of crude soybean oil is transported to refineries for further processing into refined soybean oil for human foods (Figure 2).

STORAGE

Crude soybean oil can be stored for extended periods of time in large tanks provided that it has been cooled to ambient air temperature, has limited exposure to air, and has very low moisture content. The natural antioxidants (e.g. tocopherols, tocotrienols, phosphatides) present in soybean oil provide significant protection from oxidation. However, phosphatide deposits may form on the bottom of storage tanks and transport equipment used for shipping crude soybean oil (Hammond et al., 2005). Chemical characteristics of solvent extracted soybean oil are shown in **Table 1,** which indicate very high quality due to low moisture, free fatty acid and phosphorus content. The low peroxide value and high Active Oxygen

Method (AOM; AOCS Method Cd. 12-57) stability indicate minimal oxidation occurs during the oil extraction process.

Some soybean processing plants degum crude soybean oil to produce phosphatides and market them as lecithin before shipping to refineries for further processing (Hammond et al., 2005). As a result, crude, degummed soybean oil is produced and marketed and feed grade oil for use in animal feeds. However, because there is a limited market for soy lecithin, gums are often added back to the meal in the toaster to evaporate water and improve the metabolizable energy content of soybean meal.

Table 1. *Chemical characteristics of U.S. soybean oil produced by solvent extraction (adapted from Hammond et al., 2005)*

Measure	Concentration
Moisture, %	0.08
Free fatty acids, %	0.31
Phosphorus, ppm	277
Tocopherols, ppm	1,365
Peroxide value, mEq/kg	0.96
AOM stability, h	39.8

SOYBEAN MEAL

The remaining oil extracted flakes or collets are transferred to a meal desolventizer-toaster for further processing **(Figure 1).** Steam vapor and vacuum are used to remove solvent vapor during the condensing process, and condensed solvent is recycled back to the extractor after water is removed from the hexane (Hammond et al., 2005). Next, the meal flows through a series of trays of a desolventizer-toaster. Toasting (heating) is necessary to inactivate protease inhibitors (e.g. trypsin inhibitors), which can adversely affect animal growth performance. The meal is subsequently dried to a moisture content of about 12%, cooled, ground with a hammermill to produce uniform particle size, and transferred to storage. The resulting dehulled soybean meal contains about 48% crude protein, and a residual crude fat content of about 1.5%. Some soybean processing facilities add some of the soybean hulls back to the meal before grinding, resulting in a crude protein content of of 44% to 46%. Some soybean processing facilities produce white soy flakes by using a flash desolventizer instead of a desolventizer-toaster to increase protein solubility (Hammond et al., 2005). White flakes are used to produce soy protein isolates (> 90% crude protein) and soy protein concentrates (65% crude protein) for human foods and specialized animal feeds.

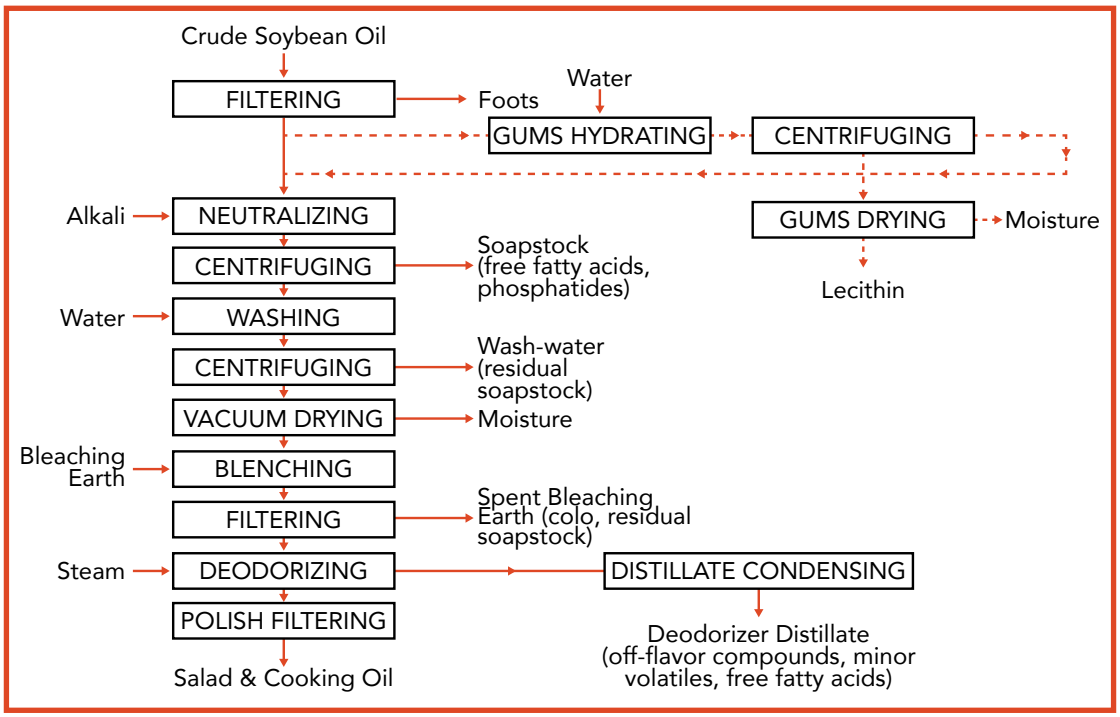

Figure 2. *Conventional soybean oil refining processes (Hammond et al., 2005)*

SUMMARY

The United States is the leading producer of soybeans globally, with about 36% of total soybean production worldwide, with over 11 million tonnes of soybean oil produced annually. Soybean oil ranks second globally among vegetable oils, which represents 26% of total oil production. Soybean processing results in the production of about 5.0 kg of crude oil, 20.1 kg of soybean meal, and about 1.5 kg of soybean hulls from each bushel (27.2 kg) processed. Solvent extraction is the most common method used to produce soybean oil in the U.S., representing over 98% of soybeans processed. Typically, soybean solvent extraction facilities are capable of processing 2,500 to 5,000 metric tonnes of soybeans per day. A significant amount of high quality U.S. crude, degummed soybean oil is produced for use in swine and poultry feeds domestically, and is exported to many countries around the world.

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Chapter

02

Advantages of Using U.S. Degummed Soybean Oil in Swine and Poultry Diets

INTRODUCTION

U.S. soybean oil has been the preferred lipid source for use in swine and poultry diets around the world for many years, and has been widely used as a benchmark for evaluating and comparing the nutritional value various quality of feed fats and oils in the global market. Soybean oil has served as a "gold standard" because of the many beneficial attributes and minimal limitations for use in swine and poultry diets that have been discovered from the extensive research conducted and published by leading animal and poultry scientists around the world. Therefore, the purpose of this chapter is to highlight the many advantages of using U.S. degummed soybean oil in swine and poultry diets with reference to various chapters in this handbook where more details and summaries of key findings from the scientific literature are described.

ABUNDANT AND CONSISTENT SUPPLY

Production of U.S. soybean oil has steadily increased during the past 20 years from about 8 million tonnes in 1999 to more than 11 million tonnes in 2019. Although much of the U.S. soybean oil produced is refined for human food grade use, significant quantities of degummed soybean oil are consistently available domestically, as well as exported to numerous countries for use in animal feeds. An abundant and consistent supply of any feed ingredient is important because once an end-user decides to commit to using a feed ingredient, assurances are needed that it will always be available to avoid the time and effort required to alter feed mill storage and handling, as well as diet formulation adjustment by switching to an alternative fat or oil source. Historically, most of the major U.S. soybean oil importing countries are located in Latin America because buyers in these countries have recognized the high value of U.S. soybean oil for a long period of time. Therefore, increased demand for U.S. refined soybean oil for human food and degummed soybean oil for animal feed use is expected to continue in the future.

COMPETITIVELY PRICED

Degummed soybean oil is one of the most digestible and highest ME sources in the global feed ingredient market. As a result, much of the high economic value from adding U.S. soybean oil to swine and poultry diets is derived from improved feed conversion resulting from its high ME content and the "extra caloric effect" commonly observed when it is added to swine and poultry diets. While crude, degummed U.S. soybean oil is typically not the lowest priced (price/tonne) oil or fat in the feed ingredient market, it is competitively priced compared to other feed fats and oils. Successful users of U.S. soybean oil realize that the true economic and nutritional value is not accurately determined based on price per kg or tonne of oil. It is more accurate to use price per Mcal of ME, along with considering the many other value-added nutritional and health benefits that U.S. degummed soybean oil provides when used in poultry and swine diets. Therefore, the true economic value of U.S. soybean oil is determined by the economic value of improved quantity, efficiency, and cost of pork, chicken, and egg production, and not on price/kg of oil, when adding it to swine and poultry diets.

For many animal feed manufacturers around the world, the personnel responsible for purchasing (procurement) of feed ingredients are focused on obtaining the best price per tonne, but usually have limited knowledge of the nutritional value and how it will be used by their nutritionists when formulating animal diets. This is sometimes referred to as the "disconnect between price and value", where the consistency of nutritional and economic value of some feed ingredients (i.e. U.S. crude degummed soybean oil) is greater than the price paid, and greater than the price of competing fats and oils in the market. Those with feed ingredient pricing and procurement responsibilities are encouraged to work with their nutritionists who

make feed formulation decisions within their company, to gain an understanding of the benefits and limitations of various fats and oils being considered for purchase. Most importantly, before purchasing feed ingredients such as U.S. soybean oil, ask the nutritionists to conduct "shadow pricing" to determine the maximum price that will make it economical to purchase and enter into various diet formulations. Several published studies and summaries have shown that high quality U.S. degummed soybean oil contains the greatest metabolizable energy (ME) content for swine and poultry compared with other common fats and oils in the market. Therefore, using accurate ME values for U.S. degummed soybean oil are essential for accurate "shadow pricing" comparisons with other feed fats and oils. This is important because lipids are purchased and used in animal diets because of their high digestible and ME content (calories), which provide an "extra caloric effect" in swine and poultry diets compared to other dietary energy sources. Although it may be difficult to quantify the economic value of the many other "value-added" features of U.S. soybean oil, they should be considered as part of the overall decision-making process. These value-added features are described in more detail later in this chapter. Therefore, good purchasing decisions for feed fats and oils should at least be based on price/Mcal of ME, and preferably based on improvements in quantity, efficiency, and cost of pork, chicken, and egg production, but not based on price/kg of oil.

WELL ESTABLISHED AND ENFORCEABLE TRADING SPECIFICATIONS

The USDA (2013) has defined the physical requirements of crude degummed soybean oil as "shall be pure soybean oil, produced from fair average quality crude soybean oil from which the major portion of the gums naturally present has been removed by hydration and mechanical or physical separation. It shall be equal in quality to soybean oil produced for domestic consumption." However, the quality and nutrient content varies for all feed ingredients, including crude, degummed soybean oil. To minimize risk of purchasing feed ingredients that do not meet expectations, trading specifications are often used for many commodities produced and marketed globally, including U.S. crude degummed soybean oil. Trading specifications are typically defined as minimum or maximum values of measurable quality indicators of specific types of feed ingredients, using internationally standardized analytical methods. For U.S. degummed soybean oil, these specifications include maximum unsaponifiable matter; maximum free fatty acid (FFA) content; maximum moisture, volatile matter, and insoluble impurities; minimum flash point; and maximum phosphorus content (Table 1). These trading specifications are used as contract guarantees to ensure that the quality of oil being purchased meets these standards. However, it is important to note that while these specifications may be useful quality indicators, they provide no information about the ME content, or extent of oxidation except for a maximum standard of < 0.75% FFA. Therefore, purchasers of U.S. degummed soybean oil are encouraged to request additional nutritional and quality indicators from their suppliers for the source being used.

Table 1. *Maximum and minimum concentrations of quality indicators of U.S. crude degummed soybean oil and approved analytical methods (adapted from USDA, 2013)*

Analyte	Maximum	Minimum	AOCS Method
Unsaponifiable matter, %	1.5	-	Ca 6a-40
Free fatty acids (as oleic), %	0.75	-	Ca 5a-40
Moisture, volatile matter, insoluble impurities, %	0.3	-	M & V Ca 2c-25
Flash point, °C	-	121	Cc 9c-95
Phosphorus, %	0.02	-	Ca 12-55

Table 2. *Price discount schedule for U.S. degummed soybean oil exceeding maximum standards for free fatty acid and phosphorus content (adapted from USDA, 2013)*

Analyte	Range	Discount
Free fatty acids, %	0.76 – 0.85	0.2% of contract price
	0.86 – 0.95	0.4% of contract price
	0.96 – 1.05	0.6% of contract price
	1.06 – 1.15	0.9% of contract price
	1.16 – 1.25	1.25% of contract price
Phosphorus, %	0.021	0.2% of contract price
	0.022	0.4% of contract price
	0.023	0.6% of contract price
	0.024	0.9% of contract price
	0.025	1.2% of contract price

Table 3. *Typical composition of crude soybean oil (adapted from Hammond et al., 2005)*

Analyte	Mean + Standard Deviation, %
Triacyglyerol	94.4 ± 1.4
Phospholipids	1.85 – 2.75
Unsaponifiable matter	1.3 – 1.6
Sterols	0.236 ± 0.053
Campesterol	0.059 ± 0.018
Stigmasterol	0.054 ± 0.013
β-Sitosterol	0.123 ± 0.027
Δ5-Avenasterol	0.005
Δ7-Stigmasterol	0.005
Δ7-Avenasterol	0.002
Tocopherols	0.123 ± 0.040
Alpha	0.0093 ± 0.0044
Beta	0.0018 ± 0.0028
Gamma	0.0834 ± 0.036
Delta	0.029 ± 0.010
Hydrocarbons	0.38
Free fatty acids	0.3 – 0.7
Trace minerals	ppm
Iron	1 – 3
Copper	0.03 – 0.05

Occasionally, the quality of the product does not meet specifications. **Table 2** shows the price discount schedule for U.S. degummed soybean oil that does not meet standard specifications for FFA and phosphorus content.

An important advantage of U.S. degummed soybean oil compared with many other fats and oils, especially blends, lipid by-products, and specialty lipids is that quality and composition specifications are well-defined and consistent. This is extremely important because nutritionists rely on consistent and predictable quality and nutritional value of feed ingredients in precision diet formulations to minimize "safety margins" in feed formulations and the risk of overfeeding or underfeeding energy in animal diets to capture the greatest economic value.

MORE CONSISTENT FATTY ACID COMPOSITION THAN OTHER LIPID SOURCES

Triacylglycerols are the primary component of crude soybean oil **(Table 3).** The unsaponifiable content of crude soybean oil averages 1.45%, and consists of 16% sterols, 8.5% tocopherols, and 26% hydrocarbons, with the remaining 50% consisting of minor and unidentified compounds (Hammond et al., 2005). The sterols are comprised of about 52% β-sitosterol, 25% campesterol, and 23% stigmasterol, whereas the tocopherols are comprised of about 7.6% alpha, 1.5% beta, 67.8% gamma, and 23.6% delta tocopherol. The relatively high concentration of tocopherols in crude soybean oil provide significant initial protection against oxidation until they are depleted, and may be responsible for minimizing the negative growth performance and health effects when oxidized soybean oil is fed to poultry and swine compared with feeding other oxidized oils (see **Chapters 3, 4, 5, and 9**). It is important to note that the FFA content ranges from 0.3 to 0.7%, which is very low compared to most other fats and oils used in swine and poultry diets. It is desirable to use lipids with low FFA content because lipids with more than 5% FFA content indicate that some oxidation has occurred and ME content may be reduced. Lastly, while iron and copper are known to accelerate lipid oxidation, the typical concentrations in crude soybean oil are low.

Fresh U.S. degummed soybean oil has a consistent fatty acid profile, which contains a high proportion of polyunsaturated fatty acids (PUFA), especially linoleic acid, which causes it to have a high ME value **(Table 4).** This consistent fatty acid profile can be attributed to the use of well-defined standardized soybean oil extraction and pro-

cessing conditions among U.S. soy crushing plants (see **Chapter 1).** Other common lipid sources in the market, such as yellow grease, animal-vegetable blends, and some sources of animal fats (e.g. poultry fat) are typically more variable in fatty acid composition because the sources and proportion of lipids used to manufacture these lipids vary among sources, processes, and over time.

However, because U.S. degummed soybean oil contains high concentrations of PUFA, it is also more susceptible to oxidation during transport and storage which can reduce its energy and feeding value for swine and poultry (see Chapters 3, 4, 5, and 9). Therefore, guidelines have been developed in this handbook to provide practical handling, transport, and storage procedures to minimize oxidation and preserve its high energy value (see Chapter 6). For example, the addition of antioxidants and frequent inventory turnover can minimize oxidation of U.S. degummed soybean oil (see Chapter 6). In fact, compared to yellow grease and animal-vegetable blends in the feed fats and oils market, fresh U.S. soybean oil has much lower indicators of oxidation (e.g. peroxide value, FFA content, p-anisidine value) after processing, which makes it a preferred lipid source in animal feeds.

Nutritionists want consistency and predictability in the nutritional value of the feed ingredients they purchase and use in diets formulations. This is essential to capture the greatest economic value by minimizing the risk of overfeeding and underfeeding energy. Therefore, U.S. soybean oil meets this goal because of its consistent composition and quality (low oxidation) compared with other feed fats and oils.

Table 4. *Average, standard deviations, and range of fatty acid composition of 21 commercial refined soybean oil samples (adapted from Hammond et al. 2005)*

Fatty acid	Mean + Standard Deviation, %	Range, %
Myristic (C14:0)	0.04±0.50	Trace – 0.03
Palmitic (C16:0)	10.57±0.43	3.2 – 26.4
Palmitoleic (C16:1)	0.02±0.04	Trace – 0.7
Stearic (C18:0)	4.09±0.34	2.6 – 32.6
Oleic (C18:1)	22.98±2.01	8.6 – 79.0
Linoleic (C18:2)	54.51±1.54	35.2 – 64.8
Linolenic (C18:3)	7.23±0.78	1.7 – 19.0
Arachidic (C20:0)	0.33±0.14	Trace – 0.7
Gondoic (C20:1)	0.18	Trace – 0.6
Behenic (C22:0)	0.25±0.20	Trace – 1.0
Lignoceric (C24:0)	0.10	-
Saponification value	190.4	188.5 – 201.6
Iodine value	132.7	114.0 – 138.5

Table 5. *Comparison of average apparent metabolizable energy (AME) values of common lipid sources used in broiler diets (adapted from Ravindran et al., 2016)*

Lipid source	AME, kcal/kg
Soybean oil	9,816
Yellow grease	9,530
Animal-vegetable blends	9,399
Poultry fat	9,005
Lard	8,151
Acidulated soybean soapstock	8,113
Tallow	7,416
Palm oil	6,999

HIGH METABOLIZABLE ENERGY CONTENT

Soybean oil is widely considered to have the greatest AME content for broilers among all common fats and oils **(Table 5).** This is due to several factors including its high polyunsaturated fatty acid (PUFA) content, low moisture, insolubles, and unsaponifiables (MIU) content, as well as its low free fatty acid (FFA) content and peroxidation. However, as for all lipids, estimates of AME content from published studies vary. Variability in these estimates are due to several factors including age of bird, unsaturated:saturated (U:S) fatty acid and FFA content, fatty acid chain length, fatty acid position on glycerol of triglycerides, and MIU content (Wiseman et al., 1991). In addition, experimental methodologies to determine AMEn also differ among reported studies, and as a result, provide variable estimates of ME content of various lipid sources. Mateos and Sell (1981) and Irandoust et al. (2012) have evaluated the benefits and limitations of using these methodologies.

Table 6. *Comparison of metabolizable energy (ME) values of common lipid sources used in swine diets (adapted from NRC, 2012)*

Lipid source	ME, kcal/kg
Flaxseed oil	8,583
Corn oil	8,579
Soybean oil	8,574
Canola oil	8,384
Restaurant grease	8,379
Poultry fat	8,364
Animal-vegetable blends	8,225
Lard	8,124
Tallow	7,835
Palm kernel oil	6,265

Table 7. *Effects of adding 5% lipid to corn-soybean meal diets on "extra caloric" effects of growing-finishing barrows (adapted from Campbell, 2005)*

Measure	0% Added Lipid	5% Added Lipid	Difference
Digestible energy, kcal/kg	3,463	3,678	6.2%
ADG, g/day	718	791	9.2%
F:G	4.21	3.74	12.6%
Carcass weight, kg	94.5	97.2	2.8%

Table 8. *Linoleic and linolenic acid content of fats and oils (adapted from Ravindran et al., 2016)*

Lipid source	Linoleic acid, %	Linolenic acid, %
Tallow	2.6	0.7
Lard	9.5	0.4
Poultry fat	20.6	0.8
Palm oil	10.0	0.4
Soybean oil	53.7	7.6
Corn oil	59.6	1.2
Canola oil	20.1	9.6

Similarly, soybean oil ranks as one of the highest ME sources among common fats and oils used in swine diets (NRC, 2012; Table 6). However, as for poultry, the high variability in ME estimates for soybean oil in swine, as well as all other lipid sources, is caused by many factors including the source, diet inclusion rate, age of pig, type of basal diet used, and extent of oxidation of the soybean oil source evaluated in these studies. Unfortunately, although several ME prediction equations have been developed for various lipids, their accuracy in predicting in vivo determined ME content is generally poor because they are too simplistic and do not include a number of important predictive variables to allow them to be useful in commercial applications. Therefore, until more accurate ME prediction equations are developed for U.S. crude degummed soybean oil, published estimates should be used (see **Chapters 8, 9, and 10**).

EXTRA CALORIC EFFECT

The addition of lipids to broiler and swine diets has often been described as having an "extra caloric effect" because it often results in greater improvement in growth rate and feed conversion above that predicted from its energy value (see **Chapter 9**). Nitsan et al. (1997) reported that the "extra caloric effect" of adding soybean oil to broiler diets is greater for low energy diets containing supplemental oil, based on body weight gain and F:G responses. When the "extra-caloric effect" is expressed on the basis of net energy retention, it is greater in diets containing 3% soybean oil than diets with 6% soybean oil. Similarly, Campbell (2005) showed that adding 5% lipid to corn-soybean meal diets fed to growing-finishing barrows provides an extra caloric effect **(Table 7).**

VALUE-ADDED BENEFITS

Using U.S. crude degummed soybean oil in swine and poultry diets has several value-added benefits beyond the calories it provides to animal diets. While the economic benefits of many of these value-added properties of U.S. crude soybean oil may be difficult to quantify, they provide additional comparative advantages compared with other feed fats and oils in the market.

HIGH ESSENTIAL FATTY ACID CONTENT

Soybean oil is the only lipid source that contains high amounts of both essential fatty acids (linoleic and linolenic acid; **Table 8**), which are required in the diets of both pigs and poultry (see **Chapters 8, 9, and 10)**. Ensuring adequate intake of essential fatty acids (linoleic and linolenic acid) during gestation and lactation of sows is essential to achieve and maintain pregnancy and increase subsequent litter

size (Rosero et al., 2016a). Similarly, essential n-3 (α-linoleic acid; 18:3 n-3) and n-6 (linoleic acid; 18;2 n-6) fatty acids are required and must be supplied in the diet for optimal embryonic development in eggs of broiler breeders Cherian, 2015).

Soybean oil is unique compared with other lipid sources because it contains high concentrations of both linoleic and linolenic acid. These fatty acids are considered to be essential and must be present in adequate amounts in the diet because animals do not have desaturase enzymes capable of adding double bonds beyond carbon 10 of octadecenoic fatty acids. However, octadecenoic acids (linoleic and α-linolenic) can be converted to long-chain polyunsaturated fatty acids by microsomal desaturase and elongase enzymes (Sprecher, 2000; Jacobi et al., 2001). Therefore, linoleic acid can be converted to ϒ-linoleic (C18:3n-6), dihomo-ϒ-linolenic (C20:3n-6), and arachidonic (C20:4n-6), and other fatty acids. Alpha-linolenic acid (C18:3n-3) can be converted to eicosatetraenoic (C20:4n-3), eicosapentaenoic (C20:5n-3), docosahexaenoic (C22:6n-3) acids, and other important long-chain fatty acids (Palmquist, 2009). These essential fatty acids are important for a number of metabolic processes including reproduction (Palmquist, 2009).

Rosero (2016b) summarized data from 6 published studies and estimated that sows fed diets without supplemental linoleic acid during lactation had a negative balance of -25.49 g/day, and a negative balance of -2.75 g/day of α-linolenic acid, which resulted in decreased farrowing rate (< 75%) and increased culling rate (> 25% in weaned sows). These effects were more dramatic as sow age (parity) increased because of a progressive reduction in essential fatty acid status during successive reproductive cycles.

Providing adequate linoleic acid intake during lactation increased the proportion of sows that farrowed and increased the number of total pigs born in the subsequent reproductive cycle. Increasing α-linolenic acid intake resulted in more rapid return to estrus after weaning (wean-to estrus interval – 4 days), sows mated:sows weaned (94%), and greater retention of pregnancy (sows pregnant:sows mated = 98%). Based on these results, Rosero et al. (2016b) concluded that the minimum dietary intake of 125 g/day and 10 g/day of linoleic acid and linolenic acid, respectively, is required during lactation to achieve optimal reproductive performance. Soybean oil can serve as an excellent source of both linoleic and linolenic acid to achieve these essential fatty acid consumption levels for optimal sow reproductive performance (see **Chapter 8**).

MINIMIZE NEGATIVE EFFECTS OF HEAT STRESS

Adding soybean oil to swine and poultry diets is also effective in minimizing reductions in growth performance under heat stress production conditions, which commonly occur in most countries around the world (see **Chapters 8 and 9**). Wolp et al. (2012) evaluated the effects of feeding isocaloric diets containing increasing levels of soybean oil (1.5, 3.0, and 4.5%), and reduced crude protein content (15.5% vs. 18%) with supplementation of adequate amounts of crystalline amino acids, on growth performance of pigs housed under heat stress conditions (32°C, 60 to 70% relative humidity) compared with a thermoneutral environment (22°C, 60 to 70% relative humidity). Results from this study showed that the high environmental temperature conditions reduced growth rate and feed conversion compared with pigs housed under thermoneutral conditions **(Table 9).** However, the addition of 4.5% soybean oil improved ADG and reduced F:G of pigs housed in heat stress conditions, compared with feeding diets containing 1.5% soybean oil, regardless of whether the dietary crude protein level was reduced. Therefore, the addition of 4.5% soybean oil to diets fed to growing-finishing pigs can be effective in partially restoring growth performance of pigs under moderate heat stress conditions.

Table 9. *Average growth rate and feed:gain responses of moderately heat-stressed pigs fed increasing dietary levels of soybean oil (SO) among high and reduced crude protein diets compared with pigs housed under thermoneutral conditions (adapted from Wolp et al., 2012)*

Measure	Control	1.5% SO	3.0% SO	4.5% SO
ADG, g	1,017	911[b]	940[ab]	985[a]
F:G	2.29	2.62[a]	2.50[ab]	2.42[a]

Similarly, Ali et al. (2001) conducted a study to determine the effects of feeding diets containing 0, 2, 4, 8, or 10% soybean oil to broilers (30 days of age) exposed to 28 to 33°C temperatures during a 15-day finisher period on growth performance. Results from this study showed that body weight gain and F:G improved by the addition of soybean oil up to 10% of the finisher diet, but was optimized at the 4% and 6% diet inclusion rates **(Table 10).** These results suggest that the addition of soybean oil to broiler diets can be effective in alleviating the negative effects on growth performance in finisher broilers raised under heat stress conditions.

Table 10. *Effects of increasing dietary soybean oil level of growth performance of finisher broilers (30 to 45 days of age) raised under heat-stress conditions (28 to 33°C; adapted from Ali et al., 2001)*

Measure	Dietary Soybean Oil Supplementation Level, %					
	0	2	4	6	8	10
Initial body weight, g	1,212	1,214	1,214	1,212	1,214	1,215
Final body weight, g	1,976[a]	2,084[c]	2,134[d]	2,173[e]	2,081[c]	2,049[b]
Body weight gain, g/15 d	764[a]	870[b]	920[c]	961[d]	867[b]	782[a]
Feed intake, g/15 d	2,423[a]	2,418[a]	2,367[ab]	2,311[b]	2,285[bc]	2,222[c]
F:G	3.17[a]	2.76[b]	2.57[c]	2.41[c]	2.64[a]	2.84[d]

Table 11. *Antioxidant capacity (Trolox equivalent) of common oils (adapted from Pellegrini et al., 2003)*

Oil source	Mmol Trolox/kg
Soybean oil	2.20
Extra virgin olive oil	1.79
Corn oil	1.29
Sunflower oil	1.17
Peanut oil	0.61

HIGHEST ANTIOXIDANT CAPACITY OF COMMON OILS

Compared to other feed fats and oils, U.S. soybean oil contains the highest concentrations of tocopherols, tocotrienols, and other natural antioxidant compounds which gives it the highest antioxidant capacity (Trolox equivalent) of several common oils used in human nutrition (**Table 11**; Pellegrini et al., 2003). The high antioxidant capacity of soybean oil is useful for minimizing oxidation during storage as well as providing benefits in swine and poultry diets for minimizing oxidative stress (see **Chapters 4, 5, and 6**).

REDUCE ADVERSE EFFECTS OF AFLATOXINS IN POULTRY

Evidence for the potential beneficial effect of supplemental oils on alleviating minimizing reductions in growth performance and livability from feeding aflatoxin contaminated diets to broilers has be reported when diets containing 16% olive oil or sunflower oil were fed, and the extent of lipid unsaturation appears to affect the magnitude of toxic effects caused by aflatoxins (Smith et al., 1971). Furthermore, the minimum toxic concentration of aflatoxins was reported to be greater in diets containing 18% supplemental lipids (Richardson et al., 1987). The addition of 3% soybean oil to aflatoxin-contaminated broiler diets has also been shown to minimize the adverse effects in growth performance (Raju et al., 2005; see **Chapter 9**).

REDUCES DUST IN FEED MILLS AND ANIMAL FACILITIES TO IMPROVE RESPIRATORY HEALTH

Adding U.S. soybean oil to mash feeds have been shown to be effective in significantly reducing dust in feed mills and animal production facilities (see **Chapter** 7). Several studies have shown that when pigs are exposed to high concentrations of dust and gases, growth and feed efficiency is often reduced (Curtis et al., 1974) and respiratory health is compromised (Doig and Willoughby, 1971; Bundy and Hazen, 1975; Drummond et al., 1981). Dust particles that are smaller than 5.2 μm in diameter are capable of penetrating the lungs of humans and pigs (Anderson, 1958), and can be carriers of viruses and bacteria (Roller, 1961; 1965; Carlson and Whenham, 1967), which causes dust to be a health concern.

IMPROVES DIET PALATABILITY TO ENHANCE FEED INTAKE

Adding U.S. soybean oil to swine and poultry diets increases diet palatability and encourages greater feed intake (see **Chapters 8, 9, and 10**).

INCREASES UNSATURATED FATTY ACIDS IN PORK, CHICKEN, AND EGG YOLKS TO IMPROVE HUMAN HEALTH

Feeding diets containing soybean oil result in increased deposition of unsaturated fatty acids in pork meat and fat, chicken, and eggs yolks, which have human health benefits compared to saturated fats (see **Chapters 8, 9, and 10**). Dietary inclusion of soybean oil in growing-finishing pig diets for 10 weeks before slaughter is effective in decreasing SFA and monounsaturated fatty acid content, and increasing PUFA content of pork muscle without adversely affecting growth performance or other carcass characteristics (Penner et al., 2018). When humans consumed pork and lard from pigs fed the control compared with these food products from pigs fed the diets containing 40% of calories from soybean oil diets in a previous study, total plasma cholesterol and LDL-cholesterol were reduced and fatty acid composition was shifted toward more PUFAs in plasma and erythrocytes (Stewart et al., 2001). As a result, eating pork from pigs fed soybean oil diets may be effective in reducing the risk of atherosclerosis and heart disease in humans. These benefits were not observed when feeding growing-finishing pig diets containing choice white grease.

Compared with other lipid sources, the addition of soybean oil to broiler diets not only improves growth performance, but also decreases the SFA content skin and abdominal fat, and increased PUFA (primarily linoleic acid) in skin, abdominal fat, and breast muscle compared with feeding poultry grease, beef tallow, or a mixture of soybean oil and poultry grease (Azman et al., 2004). Dänicke et al. (2000) showed that the proportions of palmitic acid (C16:0), oleic acid (C18:1), linoleic acid (C18:2 n-6), linolenic acid (C18:3 n-3), and docosahexaenoic acid (C22:6 n-3) increased in yolk fat with increasing soybean oil additions. The increase in n-3 fatty acids (linolenic and docosahexaenoic acids) in egg yolk has a positive effect on improving nutritional value of eggs for humans (Ferrier et al., 1994; Shafey and Cham, 1994; Farrell, 1994). Furthermore, Dänicke et al. (2000) calculated that the maximum deposition efficiency of essential fatty acids from soybean oil in egg yolk is achieved at a dietary inclusion rate of about 7%.

ENVIRONMENTAL SUSTAINABILITY OF U.S. SOY PRODUCTION

The U.S. soybean industry has developed a U.S. Soy Sustainability Protocol that is audited by third parties to verify that sustainable soybean production practices are followed. This sustainability protocol is part of the overall U.S. soybean producer environmental sustainability program that includes 4 directives:

1. Biodiversity and high carbon stock production control measures and regulations.
2. Production practice control measures and regulations
3. Public and labor health and welfare control measures and regulations
4. Continuous improvement of production practices and environmental protection control measures and regulations.

Currently, more than 95% of U.S. soybean producers participate in the U.S. Farm Program and are subject to audit. Internal audits are conducted by soybean producers and independent third-party audits are conducted annually by the U.S. Department of Agriculture. The U.S. Soy Sustainability Assurance Protocol was positively benchmarked with the European Feed Manufacturers' Federation's (FEFAC) Soy Sourcing Guidelines through the International Trade Centre. For more information about U.S. Soy Sustainability visit: https://ussec.org/wp-content/uploads/2017/11/20180416-U.S.-Soy-Sustainability-Assurance-Protocol-low-res.pdf

LIMITATIONS

There are no "perfect" feed ingredients, and the use of soybean oil in swine and poultry diets also has a few limitations.

HIGH SUSCEPTIBILITY TO OXIDATION

Because of its high concentrations of PUFAs, soybean oil is highly susceptible to oxidation when exposed to heat, oxygen, moisture, light, and transition metals such as copper and iron (see **Chapter 3**). However, oxidation can be prevented by using recommended procedures for handling, transport and storage, as well as the addition of commercial antioxidants before it is added to pig and poultry diets (see **Chapter** 7).

Minimizing lipid oxidation is extremely important because results from a recent meta-analysis study showed that the overall average effects from feeding oxidized lipids to broilers and pigs caused a 5% reduction in ADG, 3% reduction in ADFI, and a 2% reduction in G:F compared with feeding unoxidized lipids (Hung et al., 2017). Published studies showing negative effects of feeding oxidized soybean oil to nursery and growing-finishing pigs are summarized in **Chapter 5,** and studies evaluating growth and carcass quality responses from feeding oxidized soybean oil to broilers are summarized in **Chapter 9.** Unfortunately, the correlations between lipid oxidation indicative and predictive measures and energy content and swine and poultry growth performance are generally poor.

POTENTIAL REDUCTIONS IN PORK FAT FIRMNESS

Pork fat firmness is an important quality characteristic in some consumer markets around the world. Because soybean oil is high in polyunsaturated fatty acids, a high proportion of the fatty acids are directly deposited in carcass pork fat making it softer in appearance and may decrease bacon slicing yields. However, this phenomenon is not unique to soybean oil, and similar effects occur when feeding any other vegetable oil source (e.g. corn oil, canola oil) containing high concentrations of polyunsaturated fatty acids. The effects of feeding diets containing soybean oil on pork fat firmness are summarized in **Chapter 8.** Fortunately, achieving desired pork fat quality can be managed by withdrawing soybean oil from the finishing diet 3 to 5 weeks before slaughter, or setting constraints in diet formulation software to control the unsaturated:saturated fatty acid content (iodine value) of the diet.

SUMMARY

There are numerous benefits and reasons for U.S. crude degummed soybean oil to be the preferred choice among all feed fats and oils in the market. Like all feed ingredients, it is not perfect and the limitations of being highly susceptible to oxidation and its role in reducing pork fat quality can be managed using the recommendations described in the handbook.

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Chapter

03

Evaluating Quality of Feed Fats and Oils

INTRODUCTION

The quality and nutritional value of feed fats and oils varies among sources and has a direct effect on animal performance. However, unlike measures to evaluate quality of other feed ingredients, measurements of quality of feed fats and oils are complex and challenging to interpret. Quality of lipids can be evaluated by many different types of measurements but generally involves measures of oxidation. Ultimately, the goal in using quality measurements and indicators to evaluate lipids is that these measurements directly relate to the physiological responses observed. Unfortunately, our current knowledge of identifying the most appropriate chemical indicators and predictors of lipid oxidation to determine the likelihood of reduced animal performance and health is limited.

OVERVIEW OF LIPID CHEMISTRY

The term lipid is used to describe animal fats and vegetable oils which have diverse chemical structures and are insoluble in water. Oils contain a relatively high proportion of unsaturated fatty acids, are liquid at room temperature, and are of vegetable origin. In contrast, fats contain a relatively high proportion of saturated fatty acids, are solid at room temperature, and are of animal origin. Lipids are comprised of hydrocarbon chains or rings of fatty acids and steroids. Fatty acids are classified as unsaturated (containing one or more cis double bonds) or saturated (contain no double bonds). Fatty acids consist of linear, aliphatic monocarboxylic acids [R-(CH_2)nCOO-] that almost always have an even number of carbons. Lipids are primarily composed of triglycerides, but may contain other lipid compounds such as sterols (e.g. cholesterol in animal fats), waxes (i.e. esters of fatty alcohols and fatty acids with low solubility in oil), phospholipids (e.g. lecithin and cephalins which are polyhydric alcohols esterified with fatty acids and phosphoric acids), and tocopherols and tocotrienols (vitamin E compounds with antioxidant activity).

Several nomenclatures are used to describe individual fatty acids including trivial names, systematic names, and the number of carbons in the fatty acid chain followed by the number of double bonds (**Table 1**; Christie, 1982; Scrimgeour, 2005; O'Brien, 2009). The arrangement of double bonds in unsaturated fatty acids is based on the position of the double bond relative to the carboxyl carbon (e.g. linoleic acid is Δ9,12-18:2 or cys-9,12-18:2; International Union of Pure and Applied Chemistry system), or based on the position of double bonds relative to the methyl terminal of the fatty acid using either the ω (omega) or the n- ("n-minus") naming system. Using the omega or n- system, the number of carbons are counted from the methyl carbon which is considered to be position-1 (e.g. linoleic acid is 18:2 ω6 or 18:2 n-6). There are 3 major families of omega fatty acids consisting of ω3, ω6, and ω9. Nutritionally, the ω3 fatty acids of α-linoleic acid (18:3), eicosapentaenoic acid (20:5; EPA), and docosahexaenoic acid (22;6; DHA) are of high interest because they are considered essential for normal growth and health, and have been associated with reducing cardiovascular disease, inflammation, and promote normal development of brain, eyes and the nervous system (DeFilippis and Sperling, 2006; Gogus and Smith, 2010; Siriwardhana et al., 2012). Linoleic acid (18:2) and arachidonic acid (20:4) are considered as essential ω6 fatty acids because they can be metabolically converted to ω6 eicosanoids (Das, 2006), which are important cell signaling molecules. However, the ω9 fatty acids (oleic acid – 18:1 and erucic acid 22:1) are not considered essential because they can be metabolically produced from unsaturated fatty acids, do not have a ω6 double bond, and are not required in the formation of eicosanoids (Kerr et al., 2015).

Table 1. *Descriptions of common fatty acids (adapted from Kerr et al., 2015)*

Common name	No. carbons	No. double bonds	Scientific name
Formic	1	0	Methanoic acid
Acetic	2	0	Ethanoic acid
Propionic	3	0	Propionic acid
Butyric	4	0	Butanoic acid
Caproic	6	0	Hexanoic acid
Caprylic	8	0	Octanoic acid
Capric	10	0	Decanoic acid
Lauric	12	0	Dodecanoic acid
Myristic	14	0	Tetradecanoic acid
Palmitic	16	0	Hexadecanoic acid
Palmitoleic	16	1	9-hexadecenoic acid
Stearic	18	0	Octadecanoic acid
Oleic	18	1	9-octadecenoic acid
Ricinoleic	18	1	12-hydroxy-9-octadecenoic acid
Vaccenic	18	1	11-octadecenoic acid
Linoleic	18	2	9,12-octadecadienoic acid
α-Linoleic	18	3	9,12,15-octadecatrienoic acid
γ-Linolenic	18	3	6,9,12-octadecatrienoic acid
Arachidic	20	0	Eicosanoic acid
Gadoleic	20	1	9-eicosenoic acid
Arachidonic	20	4	5,8,11,14-eicosatetraenoic acid
Eicosapentaenoic	20	5	5,8,11,14,17-eicosapentaenoic acid
Behenic	22	0	Docosanoic acid
Erucic	22	1	13-docosenoic acid
Docosahexaenoic	22	6	4,7,10,13,16,19-docosahexaenoic acid
Lignoceric	24	0	Tetracosanoic acid

ANALYSIS OF LIPID CONTENT

Multiple methods have been used to determine lipid content of feed ingredients (including fats and oils), as well as diets, digesta, and feces. Analytical methods used to determine lipid content vary by solvent type (ether, hexane, or chloroform), extraction time, temperature, pressure, and sample moisture content (Kerr et al., 2015). Contrary to popular belief, crude fat analyses methods do not completely extract all fatty acids from a feed ingredient, particularly if they are chemically linked to carbohydrates or proteins, or are in the form of salts of divalent cations (NRC, 2012). Use of acid hydrolysis extraction methods appear to be more effective in releasing fatty acids from tri-, di-, and mono- acylglycerides, lipid-cabohydrate bonds, lipid-protein bonds, sterols, and phospholipids, resulting in greater extraction and analytical values

(Kerr et al., 2015). As a result, use of acid hydrolyzed ether extract procedures provides more complete lipid extraction and greater values than standard ether extract (crude fat) analysis methods (NRC, 2012; Palmquist and Jenkins, 2003; Luthria, 2004), but not always (Moller, 2010). Furthermore, lipid extraction method and type of solvent used has been shown to affect digestibility coefficients of lipids in diets and feed ingredients (Jongbloed and Smits, 1994). Therefore, buyers of feed fats and oils need to consider the most appropriate analytical method to use when determining total lipid content, and ensure that the same method is used by the supplier to comply with trading specifications and expectations.

CHEMISTRY OF LIPID OXIDATION

The lipid oxidation process is complex. Oxidation occurs when an oxygen molecule attacks an unsaturated fatty acid. Although the rate of oxygen uptake increases with greater unsaturation, the mechanisms of oxidation among different types of fatty acids vary (Holman, 1954). Lipids with high proportions of saturated (SFA) and monounsaturated fatty acids (MUFA) are relatively resistant to oxidation, but can be oxidized at a much slower rate than polyunsaturated fatty acids (PUFA). When SFA and MUFA are heated to temperatures greater than 100°C, oxygen can attack the β-carbon and produce hydroperoxides. Furthermore, the carbon chain length (Naudi et al., 2012), and the extent of unsaturation of a fatty acid on the sn-1, sn-2, or sn-3 positions of a fatty acid in the triglyceride affects the susceptibility of a fatty acid to oxidation (Lau et al., 1982; Tautorus and McCurdy, 1990; 1992; Belitz et al., 2009; Wang et al., 2005).

Holman (1954) proposed a peroxidizability index to characterize the relative susceptibility of different acyl chains of fatty acids to attack by oxygen, using an empirical measurement of oxygen consumption and a value of 1 for the rate of oxygen consumption for linoleic acid (18:2n-6; **Figure 1**). For example, DHA contains 6 double bonds causing it to be 8 times more susceptible to oxidation than linoleic acid, which has 2 double bonds. By combining the relative susceptibility of different fatty acids to oxidation with the fatty acid composition of a lipid source, the total peroxidizbility index of a lipid **(Table 2)** can be calculated as: Peroxidizability index = [(0.025 × % monoenoics) + (1 × % dienoics) + (2 × % trienoics) + (4 × % tetraenoics) + (6 × % pentaenoics) + (8 × % hexaenoics). However, Belitz et al., 2009) suggested a greater effect of the extent of unsaturation of a fatty acid with relative oxidation rates of 1, 100, 1,200, and 2,500 time greater for 18:0, 18:1, 18:2, and 18:3 fatty acids, respectively. It is important to note that this approach only accounts of oxygen uptake by fatty acids and does not consider various lipid oxidation products that are produced.

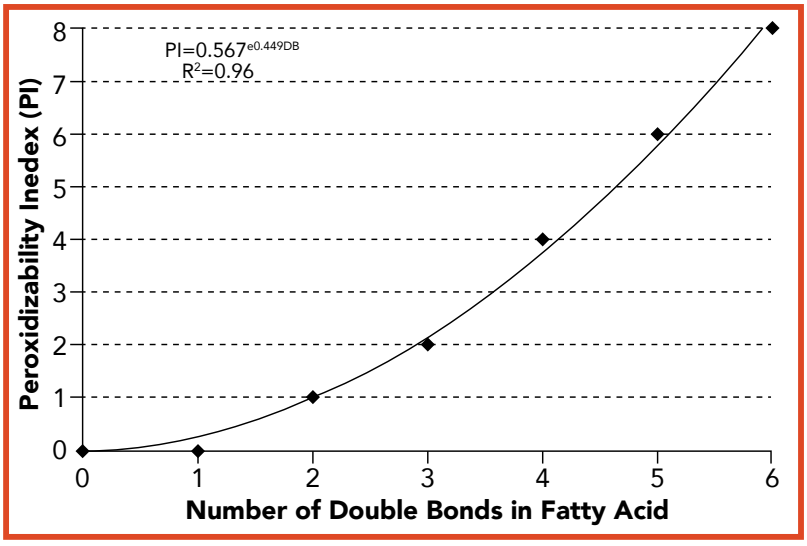

Figure 1. *Relative susceptibility of double bonds in unsaturated fatty acids to oxidation (adapted from Holman, 1954).*

Lipid oxidation is a dynamic process that produces and degrades numerous oxidation compounds over time (Frankel, 2005; Labuza and Dugan, 1971; Gutteridge, 1995; St. Angelo, 1996; Nawar, 1996). In general, the oxidation process is described in 3 phases. The initiation phase involves the formation of free radicals and hydroperoxides. Oxidation is promoted by exposure to oxygen, transition metals (iron and copper), undissociated salts, water, and other non-lipid compounds (Halliwell and Chirico, 1993; Frankel, 2005; Schaich, 2005). The second phase is referred to as the propagation phase where the previously formed hydroperoxides are decomposed into secondary oxidation products, which consist primarily of aldehydes and ketones, hydrocarbons, furans, and volatile organic acids (Shurson et al., 2015). The last phase is called the termination phase which involves the formation of tertiary oxidation products such as polymers and epoxy compounds (Shurson et al., 2015). As the oxidation process progresses through these 3 phases over time, oxygen consumption continues to increase, as well as the production of volatile and non-volatile compounds and free fatty acids, while the concentration of unsaturated fatty acids decreases (Labuza and Dugan, 1971). In the initiation phase, production of hydroperoxides increase but are subsequently degraded to aldehydes during the subsequent phases. **Figure 2** shows the relative production and degradation of peroxides and aldehydes over time, with increasing production of acids and polymers as oxidation progresses. In fact, at least 19 volatile compounds are formed during oxidation of linoleic acid (Belitz et al., 2009). Therefore, due to the continual changes in production and degradation of various oxidation products over time, it is difficult to quantify the extent of lipid oxidation. As a result, there is no single oxidation indicator method that adequately characterizes the extent of lipid oxidation, and requires using multiple oxidation indicator tests.

Table 2. *Peroxidizability index of various lipids (adapted from Kerr et al., 2015)*

Lipid	Peroxidizability Index1[1]
Coconut oil	2
Tallow	5
Palm oil	12
Olive oil	13
Lard	15
Poultry fat	23
Canola oil	40
Sunflower oil	41
Corn oil	57
Soybean oil	65
Flaxseed oil	120
Menhaden fish oil	214
Algae oil	258

[1]Peroxidizability index = [(0.025 x % monoenoics) + (1 x % dienoics) + (2 x % trienoics) + (4 x % tetraenoics) + (6 x % pentaenoics) + (8 x % hexaenoics) from Holman (1954).

ANALYTICAL MEASURES OF LIPID QUALITY AND OXIDATION

Many different analytical tests are used to determine lipid quality. Unfortunately, most of the common measurements used for feed fats and oils trading specifications do not provide accurate and meaningful information about their actual energy and feeding value (Table 3). Color of a fat or oil is quantified based on the Fat Analysis Committee (FAC) standard, ranging from 1 (light) to 45 (dark). However, color is a poor indicator of lipid quality and feeding value. Titer is defined as the temperature at which a lipid becomes solid, whereas saponification value is an estimate of the average molecular weight of fatty acids in a sample. Insolubles are the foreign material in a sample that causes sediment at the bottom of lipid storage tanks.

Unsaponifiables are a measure of compounds in a lipid that will not form soap when mixed with caustic soda (NaOH or KOH), and generally includes sterols, hydrocarbons, pigments, fatty alcohols, and vitamins.

Figure 2. *Relative rate of production and degradation of major oxidation products over time (adapted from Fitch Haumann, 1993).*

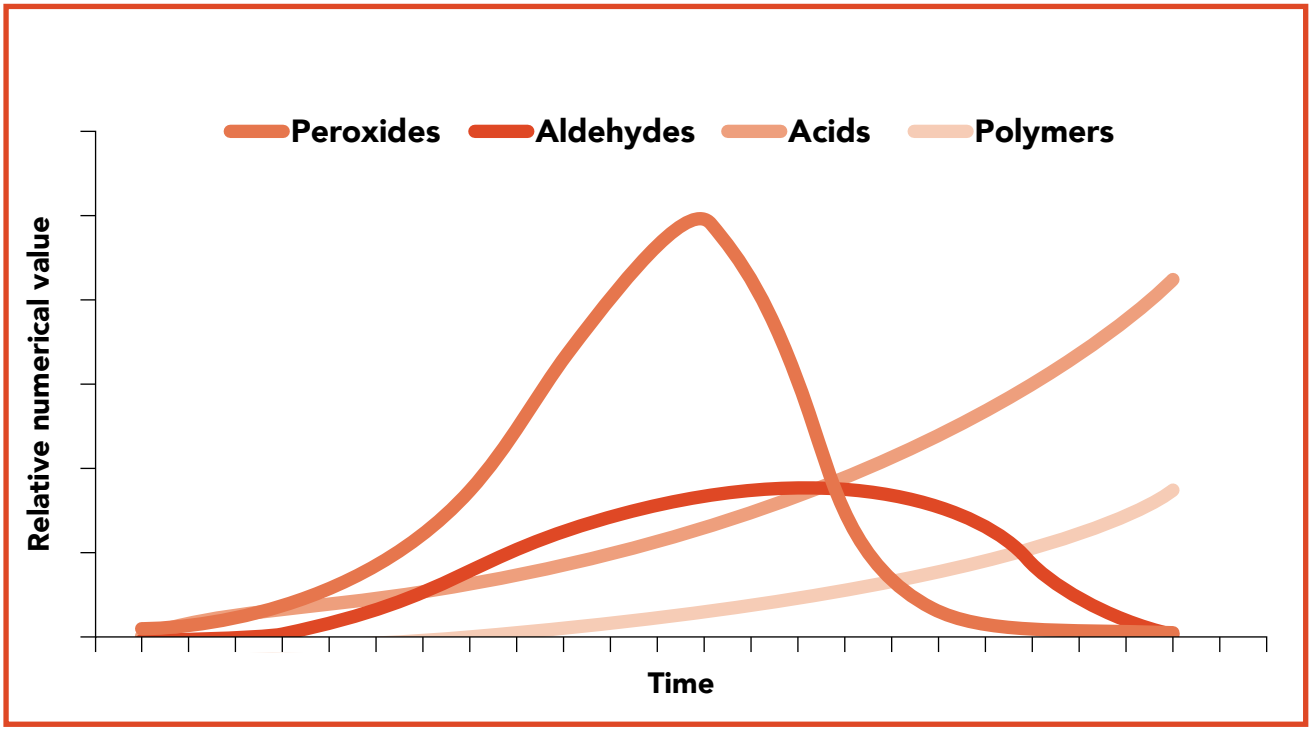

Table 3. *Common lipid quality measurements used for trading specifications (adapted from Shurson et al., 2015).*

Lipid quality measure	Comments
Color	Subjective, non-specific, and a poor indicator of oxidation and energy value. Lipid color is not correlated with energy or feeding value of lipids.
Change in fatty acid profile	Subjective, non-specific, and of limited practical use due usual lack of original composition data prior to oxidation. Fatty acid profiles may provide some general evidence of lipid quality, but do not accurately represent the amount of oxidation that has already occurred.
Increase in free fatty acid content	Subjective, non-specific, and of limited practical use due usual lack of original composition data prior to oxidation. Although studies have generally showed that as free fatty acid content increases, digestible energy content decreases in lipids, recent studies have shown that this is not always the case, because it depends on which free fatty acids are increased. Some acid oils (soy acid oil) contain high concentrations of FFA but do not have reduced energy content.
Decreased titer, iodine value, unsaturated:saturated fatty acids	Subjective, non-specific, and of limited practical use due usual lack of original composition data prior to oxidation. Measures of the proportion of unsaturated:saturated fatty acids in a lipid source provide a general indication of susceptibility to oxidation, but are not accurate indicators of actual oxidation that may have occurred.
Saponification value	This measure allows comparison of the average fatty acid chain length, which provides similar information as iodine value, but is not indicative of the extent of oxidation.
Moisture, Insolubles, and Unsaponifiables	While these common measurements are quantitative, the concentrations are generally low in most lipids and have minimal effects on energy content. However, higher concentrations may be predictive of susceptibility to further oxidation over time.

Several analytical methods can be used to evaluate lipid oxidation and stability, and can be categorized as indicative or predictive tests. Indicative tests measure specific chemical compounds, or chemically related compounds present in a lipid at the time of sampling, and provide some insight of the relative extent

that oxidation has occurred. In contrast, predictive tests assess the susceptibility of a lipid to oxidation when exposed to standardized conditions used to promote oxidation.

LIPID OXIDATION INDICATOR TESTS

In most situations, animal nutritionists are interested in determining the extent of lipid oxidation in existing fats and oils being used in diet formulations. This information can be used to assess the relative risk of reductions in animal performance and health when added to diets.

Table 4. *Lipid oxidation indicator tests, compound measured, and limitations (adapted from Shurson et al., 2015)*

Oxidation indicator	Oxidation compounds measured	Limitations
Peroxide value (PV)	Peroxides and hydroperoxides	Only measures oxidation products during the initiation phase, which are quickly degraded during continuous oxidation conditions. Subjective and peroxides may be undetected in lipids exposed to > 150°C. May be useful when considered in combination with TBARS and AnV.
Thiobarbituric acid reactive substances (TBARS)	Malondialdehyde	Not specific to malondialdehyde because 2-alkenals and 2,4-alkedienals can react with thiobarbituric acid. Different methodologies make inter-laboratory comparisons difficult.
Anisidine value (AnV)	Aldehydes	Not specific to a specific aldehyde because 2-alkenals and 2,4-alkedienals can react with *p*-anisidine under acid conditions.
Conjugated dienes	Primary peroxidation compounds formed after a double bond rearrangement in peroxides	Less sensitive compared with PV. Carotenoids are absorbed in the same wavelength range which can lead to misleading results for some lipids.
TOTOX value	Sum of AnV (or TBARS) and 2 × PV. Measures both primary and secondary oxidation compounds.	Increases the lack of specificity inherent with AnV (or TBARS) and PV.
Carbonyls	Secondary oxidation compounds including aldehydes and ketones.	Lack of specificity and tendency to be influenced by non-carbonyl compounds.
Hexanal	Specific carbonyl compound formed during the termination phase of the oxidation process when linoleic acid (C18:2 n-6) or other n-6 fatty acids are oxidized.	Volatile at high tempertures and may provide misleading information on the extent of oxidation.
2,4-decadienal (DDE)	Specific aldehyde derived from linoleic acid (C18:2 n-6) during oxidation.	Complicated and expensive assay requiring gas chromatography and mass spectrophotometry.
4-hydroxynonenal (HNE)	α, β-unsaturated lipophilic aldehyde formed during lipid oxidation of n-6 polyunsaturated fatty acids (i.e arachidonic and linoleic acid).	Complicated and expensive assay requiring LC-MS equipment.
Triacylglygerol dimers and polymers	Polymeric compounds formed during the late phases of oxidantion	Expensive assay using size exclusion chromatography. Limited information on their effects on animal health and performance.
Oxiranes	Cyclic compounds produced during oxidation	Assay is not specific to oxiranes because it can also detect carbonyls and conjugated dienes.
Non-elutable material	Determined using a gas-liquid chromatography procedure that estimates non-elutable material of a lipid aftr a correction for glycerol.	Difficult method to implement. Non-specific assay that collectively measures most degraded chemical structures of a lipid.

Liu et al. (2014) determined correlations among lipid oxidation predictive and indicative measures and chemical composition of 4 lipid sources (corn oil, canola oil, poultry fat, and tallow) using 3 different time and temperature conditions to create oxidation. However, it is important to remember that significant correlations do not infer cause and effect relationship. Moisture, insolubles, and unsaponifiables (MIU) was positively correlated with OSI (r = 0.81, 0.78, and 0.70, respectively). Peroxide value was positively

associated with TBARS, hexanal, and DDE (r = 0.75, 0.76, and 0.61, respectively). Anisidine value was positively correlated with HNE (r = 0.67) and AOM (r = 0.53), but negatively with OSI (r = -0.57). Other positive correlations were between TBARS and AOM (r = 0.51), hexanal and DDN (r = 0.94) and AOM (r = 0.57), DDE and HNE (r = 0.49) and AOM (r = 0.65), HNE and AOM (r = 0.66). There was also a negative correlation between AOM and OSI (r = -0.58). The lack of several correlations among oxidation measures is like due to the varying extent of production of primary, secondary, and tertiary oxidation products over time under differing oxidation conditions and lipids evaluated. Therefore, accurate determination of the extent of oxidation in lipids requires using multiple sampling time points and multiple indicator tests. Peroxide value is routinely determined in commercial laboratories and is a useful measure to assess lipid quality in the early stage of oxidation because most hydroperoxides have not been decomposed to aldehydes. The use of TBARS and AnV are reasonably accurate measures to assess aldehyde concentrations in extended oxidation time periods. Determining free fatty acid concentration is also a useful general indicator of the extent of lipid oxidation.

Wang et al. (2016) used liquid chromatography-mass spectrometry, principal component analysis, and hierarchical cluster analysis to evaluate the kinetics of aldehyde formation in heated frying oils (soybean, corn, and canola oils). Results of this study showed that the concentrations of pentanal, hexanal, acrolein, and an aldehyde ratio were highly correlated with extent of thermal oxidation, and 4-HNE was highly correlated with extent of thermal oxidation in soybean oil. While these results are promising for enhancing our ability to more accurately quantify the extent of oxidative damage of fats and oils, the cost and complexity of using this analytical equipment and procedures limit the commercial applicability of using this approach.

LIPID OXIDATION PREDICTIVE TESTS

At times, animal nutritionists may want to know the susceptibility of a lipid source to oxidation when deciding if they want to use it. Measurements used to predict the capability of a lipid to be oxidized when exposed to standardized, accelerated oxidation conditions include active oxygen method (AOM), oil stability index (OSI), and oxygen bomb method (OMB). All of these methods involve exposing lipid samples to accelerated conditions of elevated temperatures and oxygen addition during an extended period of time and measure the amount of lipid oxidation products. For AOM, oxygen is bubbled through a lipid sample and iodine value or peroxide value is measure over time. Oil stability index is measured by heating a lipid sample to at least 100°C while air is bubbled through it, and the volatile compounds that are produced are transferred to a water trap where conductivity is measured. Similarly, for the OMB method, a sample of lipid is oxidized at 100°C with pure oxygen at high pressure for several hours to measure the pressure drop over time.

All of these methods have limitations. The AOM method 1) requires a significant length of time to conduct the assay, especially for stable lipids (Shermer and Zhing, 1997), 2) involves several modified procedures which makes it difficult to compare values among laboratories (Jebe et al., 1993), and has been suggested to be an outdated method (Shahidi and Zhong, 2005). The OSI method has several advantages compared to the AOM method, which has generally made it the most preferred predictive test because 1) it provides the capability of analyzing multiple samples simultaneously, 2) is highly correlated with AOM (Läubli et al., 1986), and is repeatable among laboratories (Jebe et al., 1993). Compared with the AOM and OSI method, the OMB assay 1) can be used for samples without lipid extraction (Gearhart et al., 1957), and 2) is generally faster and highly correlated with the AOM method, but requires extra time when evaluating relatively stable samples (Pohle et al., 1963).

CAN WE USE LIPID OXIDATION MEASURES TO PREDICT ANIMAL GROWTH PERFORMANCE?

The ultimate goal of determining the extent of oxidation of lipids is to use these indicator values to predict effects on energy content and animal performance. Unfortunately, the correlations between lipid oxidation indicative and predictive measures and energy content and swine and poultry growth performance are generally poor.

Lindblom et al. (2018) compared the chemical composition of fresh, unoxidized U.S. soybean oil to soybean oil oxidized under 3 conditions: 1) heated at 45°C for 288 hours; 2) heated at 90°C for 72 hours; and 3) heated at 180°C for 6 hours, with all treatments exposed to air at a rate of 15L/minute. No antioxidants were added before or after heating. Free fatty acid (FFA) content is usually increased after lipids are exposed to heat, but FFA content did not change substantially with increased temperatures used in this study. However, peroxide value increased when oils were heated at 45°C for 288 hours, and further increased when heated at 90°C for 72 hours, but then declined to a low concentration when oil was heated at 180°C for 6 hours. This suggests that initial peroxide products were degraded and began forming secondary and tertiary oxidation compounds in the oil heated at 180°C for 6 hours. Compared with thiobarbituric acid reactive substances (TBARS), which changed very little with increasing thermal treatment, anisidine value, which is a unit-less measure of high molecular weight aldehydes, was found in the highest concentrations in oils heated at 90°C and 180°C. All of the aldehydes were dramatically increased in oils heated at 90°C and 180°C, as well as were the polymerized triacylglycerides. Although total tocopherol content declined among the 3 thermal treatments, the amount of loss was not as great as may have been expected. These results show that substantial oxidation of soybean oil occurs at temperatures of 90°C and 180°C. However, thermal processing of soybean oil at different times and temperatures had minimal effects on energy, lipid, and nitrogen digestibility, and had no effect on intestinal permeability of growing pigs in this study. Although significant correlations were observed between various soybean oil quality indices and energy and nutrient digestibility responses, they were relatively low (r = -0.24 to -0.51). Peroxide value had the greatest negative correlation with DE:GE (r = -0.40), polymerized triacylglycerides had the greatest negative correlation with lipid digestibility (r = -0.51), and anisidine value, hexanal, and 4-hydroxynonenal had the greatest negative correlations (r = -0.43) with nitrogen retention. Therefore, our ability to energy and nutrient digestibility responses of pigs fed oxidized soybean oil using various indicators of oxidation is poor. When these diets were fed to barrows from 25 to 71 kg body weight, ADG was similar among pigs fed soybean oil processed at 22.5 °C, 45 °C, and 180 °C, which were greater than pigs fed the 90 °C thermally processed soybean oil diet (Lindblom et al., 2018). These results are consistent with the high amount of oxidation products for this oil source, and the reduced energy and lipid digestibility and nitrogen retained. However, it was somewhat surprising that feeding the soybean oil source thermally oxidized at 180 °C had no effect on ADG even though it had the second greatest amount of oxidation products compared with the soybean oil source heated at 90 °C. Feeding oxidized lipids typically reduces ADFI (Hung et al., 2017), but there were no differences among oxidized soybean oil treatments in this study. Furthermore, feeding oxidized lipids to pigs generally results in reductions in Gain:Feed (Hung et al., 2017), but there were no differences among treatments, except that feeding the 45 °C heated soybean oil resulted in greater Gain:Feed compared with other treatments. Similar to energy and nutrient digestibility correlations, significant correlations were observed between various soybean oil quality indices and growth performance traits, but they were relatively low (r = -0.26 to -0.47). Polymerized triacylglycerides had the greatest correlation with ADG (r = - 0.47), peroxide value and oxidized fatty acids were the only quality indicators correlated with ADFI (r = -0.28), and the aldehyde ratio had the highest correlation (r = -0.35) with Gain:Feed responses. Therefore, our ability to predict growth performance responses of pigs fed oxidized soybean oil using various indicators of oxidation is poor.

In a similar study involving the same thermally oxidized soybean oil treatments, Overholt et al. (2018) reported low positive correlations ($r < 0.33$) for unsaturated:saturated fatty acids and tocopherol content with ADG and Gain:Feed of finishing pigs, and low negative correlations ($r < -0.35$) for peroxide value, total polar compounds, hexanal, and HNE with these growth performance measures. However, no significant correlations between anisidine value, oxidized fatty acids, polymerized triglycerides, oil stability index, acrolein, and 2,4-decadienal with ADG and Gain:Feed were observed.

In broilers, Lindblom et al. (2019) evaluated the effect of oil source (palm oil, soybean oil, flaxseed oil, fish oil) and peroxidation status (fresh or peroxidized) on growth performance and oxidative stress. Several interactions between oil source and peroxidation status were observed. First, ADG, ADFI, G:F, and plasma glutathione peroxidase were reduced in all oil sources except fish oil. Second, liver TBARS tended to increase in birds fed peroxidized palm oil compared to those fed fresh palm oil. Third, liver protein carbonyl concentrations were similar for broilers fed palm, flaxseed, and fish oil regardless of peroxidation status, but birds fed peroxidized soybean oil had increased liver protein carbonyl concentrations compared to those fed fresh soybean oil. Results from this study suggest that the high correlations between oil composition, growth performance, and oxidative stress biomarkers indicate that UFA:SFA, p-anisidine value, 2,4-decadienal (DDE), total polar compounds, and polymerized triglyceerides should be measured as key indicators of oil quality. Growth performance responses were correlated with plasma TBARS, protein carbonyls, and glutathione peroxidase.

Hung et al. (2017) conducted a meta-analysis of results from 29 published studies involving feeding isocaloric diets containing various sources of oxidized and unoxidized lipids to broilers and growing pigs on growth performance. A total of 42 observations for broilers, and 23 observations for swine, were compared to assess the overall effects of feeding oxidized versus unoxidized lipids on growth performance. Lipid sources reported in these studies included animal-vegetable blends ($n = 5$), beef tallow ($n = 3$), canola oil ($n = 2$), choice white grease ($n = 4$), corn oil ($n = 10$), fish oil ($n = 2$), poultry fat ($n = 9$), soybean oil ($n = 24$), sunflower oil ($n = 5$), and vegetable oil ($n = 1$). Correlations between dietary peroxide value and TBARS content reported in these published studies with specific growth performance measures were determined. Although dietary peroxide values was significantly negatively correlated with ADG ($r = -0.81$), ADFI ($r = -0.79$), and G:F ($r = -0.77$) in broilers, it was not correlated with swine growth performance measures. However, these relatively high correlations for poultry should be interpreted with caution because they were heavily influenced by a few extreme data points. For swine, dietary TBARS values were negatively correlated with ADG ($r = -0.58$), and tended to be negatively correlated with ADFI ($r = -0.46$) and G:F ($r = -0.47$). These results suggest that a combination of different oxidation measures must be used for predicting growth performance responses of pigs and broilers when fed lipids of varying extent of oxidation.

SUMMARY

Determination of the extent of oxidation in various lipid sources is challenging because of the complexity of the oxidation process, production of numerous types of oxidation products, and the limitations of using various indicative and predictive tests. Although the use of liquid chromatography-mass spectrometry chemometrics allows for identifying and quantifying various oxidation products, this approach is not currently used in commercial laboratories. Therefore, multiple indicative tests must be used to attempt to assess the extent of lipid oxidation and should include peroxide value (hydroperoxides), anisidine value or TBARS (aldehydes), and free fatty acid content. Correlations among individual indicative and predictive tests with energy content, nutrient digestibility, and animal performance measures (e.g. ADG, ADFI,

Gain:Feed) is generally poor in individual published studies. However among studies, negative correlations between peroxide value and ADG, ADFI, and Gain:Feed in broilers appears to be moderately high, but not for swine. In contrast, TBARS appears to be negatively correlated with ADG and tends to be negatively correlated with ADFI and Gain:Feed for swine, but the correlations are modest ($r < -0.60$). Furthermore, no significant correlations between TBARS and growth performance measures in broilers were observed. Reasons for these differences in correlations for swine and broilers is unclear.

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Chapter

04

Consequences of Feeding Oxidized Lipids to Poultry and Swine

INTRODUCTION

Many sources of lipids are fed to swine and poultry that vary substantially in energy content, quality, and cost. In addition to the fatty acid profile of feed fats and oils, lipid quality, as defined by the extent of oxidation, has similar effects on energy content and animal performance. Industry surveys have shown that lipid oxidation, measured by peroxide value (PV) can range from 0.1 to 181 mEq O2/kg lipid (Dibner et al., 2013; personal communication). In addition, a substantial amount of frying oils from restaurants are commonly added either directly into animal diets, or blended with rendered animal fats to produce animal-vegetable blends (Kerr et al, 2015; van Heugten et al., 2016). The high temperatures and extended time of heating of these frying oils results in extensive oxidation, and can result in a PV as high as 248 mEq O2/kg oil (Rosero, et al., 2015).

Numerous studies have shown that feeding oxidized lipids to poultry and swine often results in a reduction in energy digestibility (Engberg et al., 1996; Inoue et al., 1984), growth rate (Boler et al., 2012; Liu et al., 2014a; Rosero et al., 2015), feed conversion (McGill et al., 2011a,b; Tavarez et al., 2011), and impaired immune function (Dibner et al., 1996; Liang et al., 2015; van Heugten et al., 2016), while increasing oxidative stress (Boler et al., 2012; Liu et al., 2014c) and mortality (Anjum et al., 2004; Tahashaki and Akiba, 1999; van Heugten et al., 2016). Furthermore, genetic improvements for faster growth rates, increased lean and breast muscle of broilers, along with heat stress and feeding oxidized lipid diets cause extensive oxidative stress in tissues (Zhang et al., 2011; Ismail et al., 2013). Oxidative stress causes damage to biological systems and pathological conditions that impair growth of broilers (Fellenberg and Speisky, 2006). However, the magnitude of these responses are variable because the fatty acid profiles of lipids affect their relative susceptibility to oxidation, as well as the poor association between individual indicator measures of lipid oxidation with animal growth performance and physiological oxidative status (Kerr et al., 2015). Therefore, our ability to predict animal growth responses from feeding oxidized lipids is challenging because of these inherent complexities.

In addition, lipid oxidation is considered a major concern regarding the quality of processed poultry products and the potential effects of oxidized foods on human health (Estévez, 2015). Although beef has been shown to be more susceptible to lipid oxidation than pork and poultry, poultry muscle contains relatively high amounts of unsaturated fatty acids which causes it to be very sensitive to oxidation (Min et al., 2008). In addition, several studies have shown that the function, texture, and digestibility of meat proteins are adversely affected by protein oxidation (Lund et al., 2011; Estévez, 2011). Therefore, lipid and protein oxidation are major concerns in both fresh and processed poultry meat leading to health concerns, reduced consumer acceptance, and economic losses (Xiao et al., 2011; Estévez, 2011; Lund et al., 2011; Bekhit et al., 2013).

Therefore, the purpose of this chapter is to describe the current knowledge of the impact of feeding oxidized lipids from various sources on 1) metabolizable energy (ME) content; 2) growth performance of broilers and pigs; 3) egg production performance of layers; 4) impacts on the immune system and oxidative stress on swine and poultry; 5) correlations between indicator lipid oxidation measures on these performance and health status responses; and 6) impact of feeding oxidized lipids on poultry meat quality.

EFFECTS OF LIPID OXIDATION ON LIPID DIGESTIBILITY AND METABOLIZABLE ENERGY CONTENT

Feeding oxidized lipids has been shown to reduce lipid and energy digestibility in pigs (Liu et al., 2014b; Lindblom et al., 2018b; Yuan et al., 2007) and broilers (Inoue et al., 1984; Engberg et al., 1996). However, results are inconsistent among the limited published studies. For example, feeding oxidized choice white grease (peroxide value = 105 mEq/kg) decreased feed intake, but did not affect lipid digestibility in pigs (DeRouchey et al., 2004). Furthermore, Liu et al. (2014b) reported no effect of feeding slow or rapidly oxidized corn oil, canola oil, poultry fat, or tallow on apparent total tract digestibility of lipid nor digestible energy (DE) and ME content of lipids fed to nursery pigs. These inconsistent and unpredictable responses are likely due to differences in lipid source fatty acid profile and susceptibility to oxidation, extent of oxidative damage, and the indicator methods used to assess oxidative damage.

GROWTH PERFORMANCE RESPONSES FROM FEEDING OXIDIZED LIPIDS TO BROILERS AND PIGS

The magnitude and direction of growth responses from feeding oxidized lipids to pigs and broilers have also been inconsistent among published studies. Therefore, Hung et al. (2017) conducted a meta-analysis of results from 29 published studies involving feeding isocaloric diets containing various sources of oxidized and unoxidized lipids to broilers and growing pigs on growth performance. A total of 42 observations for broilers, and 23 observations for swine, were compared to assess the overall effects of feeding oxidized versus unoxidized lipids on growth performance. Lipid sources reported in these studies included animal-vegetable blends (n = 5), beef tallow (n = 3), canola oil (n = 2), choice white grease (n = 4), corn oil (n = 10), fish oil (n = 2), poultry fat (n = 9), soybean oil (n = 24), sunflower oil (n = 5), and vegetable oil (n = 1).

None of these studies reported an increase in growth performance, and the majority of 65 observations showed no difference in average daily gain (ADG; 51%), average daily feed intake (ADFI; 74%), and gain:feed (G:F; 74%) when comparing combined broiler and pigs responses from feeding isocaloric diets containing either oxidized and unoxidized lipids **(Table 1).** These inconsistent responses can be attributed to variation in fatty acid profiles among lipid sources, dietary inclusion rate of lipids, extent of oxidation, methods used to cause lipid oxidation, inaccurate methods to determine extent of oxidation, and inadequate replication among studies (Hung et al., 2017). However, the overall average effects from feeding oxidized lipids to broilers and pigs resulted in a 5% reduction in ADG, 3% reduction in ADFI, and a 2% reduction in G:F compared with feeding unoxidized lipids (Hung et al., 2017). A reduction in gain efficiency (G:F) has been shown in several studies (Anjum et al., 2004; Cabel et al., 1988; Ehr et al., 2015; Hanson et al., 2016; McGill et al., 2011a, b: Tahashaki and Akiba, 1999; Tavarez et al., 2011), but not in several other studies (Açikgöz et al., 2011; Bayraktar et al., 2011; Liu et al., 2014a, Oldfield et al., 1963; Racanicci et al. 2008: Rocha et al., 2012; Rosero et al., 2015, Upton et al., 2009; van Heugten et al., 2016).

However, of the studies reporting reductions in growth performance, the most extreme percentages of reduction in growth performance were a 50% reduction for ADG, 70% reduction for ADFI, and 70% reduction for G:F. In these studies, the reduction in ADG was a result of decreased ADFI, which was independent of caloric content because these diets were isocaloric. Therefore, the reduction in ADFI was likely due to reduced diet palatability cause by the odor and flavor of aldehydes produced during the lipid oxidation process (Esterbauer et al., 1991: Halliwell and Chirico, 1993). The reduction in G:F reported in these studies may be related to increased oxidative stress because feeding

oxidized lipids has been show to impair immune function (Dibner et al., 1996), and cause erythrocyte dysfunction and increase oxidative stress (Rosero et al., 2015).

Table 1. *Summary of growth responses from feeding isocaloric diets containing oxidized lipids to broilers and growing pigs (adapted from Hung et al., 2017)*

Measure	No. observations	Response to feeding oxidized lipids			
		Increase	Decrease	No change	Not reported
ADG	65	0	27	33	5
ADFI	65	0	12	48	5
G:F	65	0	17	48	0

Because of the complexity of the oxidation process, the multiple oxidation products that are produced and degraded over time, and the specificity of oxidation products measured with various indicator assays, our ability to use these oxidation indicator measurements to accurately predict reductions in animal growth performance is limited. As a result, using a single measurement of lipid oxidation is insufficient for predicting animal growth performance.

Hung et al., (2017) determined correlations between dietary PV and thiobarbituric acid reactive substances (TBARS) content reported in published studies with specific growth performance measures. Although dietary peroxide values was significantly negatively correlated with ADG (r = -0.81), ADFI (r = -0.79), and G:F (r = -0.77) in broilers, it was not correlated with swine growth performance measures. However, these relatively high correlations for poultry should be interpreted with caution because they were heavily influenced by a few extreme data points. For swine, dietary TBARS values were negatively correlated with ADG (r = -0.58), and tended to be negatively correlated with ADFI (r = -0.46) and G:F (r = - 0.47). These results suggest that a combination of different oxidation measures must be used for predicting growth performance responses of pigs and broilers when fed lipids of varying extent of oxidation.

EFFECTS OF FEEDING OXIDIZED LIPIDS ON OXIDATIVE STATUS OF BROILERS AND PIGS

The negative effects of oxidative stress on animal health is well-established (Lykkesfeldt and Svendsen, 2007), where it has been shown to impair optimal immune and gut barrier function resulting in increased risk of pathogenic infection (Machlin and Benrich, 1987). Furthermore, oxidative stress causes various metabolic disorders and congestive heart failure in birds (Fathi et al., 2011), along with negative effects on poultry meat quality including pink color (Holownia et al., 2003), woody breast (Sihvo et al., 2013), and white striations in broiler breast muscle (Kuttappan et al., 2013).

Oxidative stress in pigs and broilers generally increases when feeding oxidized lipids. Hung et al. (2017) summarized responses from several published studies evaluating vitamin E and TBARS concentrations, and glutathione peroxidase (GPx) activity in pigs and broilers fed oxidized lipids compared to those fed unoxidized lipids **(Table 2).** Serum and tissue vitamin E concentrations are indicators of oxidative status, and have been shown to decrease when oxidized lipids have been fed to pigs (Boler et al., 2012; Hanson et al., 2016; Liu et al., 2014c) and broilers (Tahashaki and Akiba, 1999; Tavarez et al., 2011). Hung et al. (2017) reported that feeding oxidized lipids to broilers and swine resulted in an average reduction in serum or plasma vitamin E content by 52% compared with those fed unoxidized lipids. This reduction in

vitamin E status can be attributed to the degradation of vitamin E present in oxidized lipids, reduced feed intake (Liu et al., 2014a), impaired absorption, or increased metabolic utilization (Liu and Huang, 1995).

Thiobarbituric acid reactive substances (TBARS) are another useful indicator of oxidative status, where increased concentrations indicate oxidative stress. Feeding diets containing oxidized lipids have been show to increase the concentrations of serum or liver TBARS in pigs (Boler et al., 2012) and broilers (Anjum et al. 2004; Lin et al, 1989; Tahashaki and Akiba, 1999). Hung et al. (2017) summarized that feeding oxidized lipids to broilers and swine resulted in an average increase of 20% in serum TBARS concentration compared with feeding unoxidized lipids. Rosero et al., (2015) reported that feeding highly oxidized lipids increases the concentration of malondialdehyde in the jejunal mucosa of the small intestine of pigs, and reduces the intestinal mucosal antioxidant capacity. Therefore, the combined effects of reduced vitamin E status and increased serum TBARS indicate an increase in oxidative stress in these studies.

Bayraktar et al. (2011) and Upton et al. (2009) reported that the production of GPX increases in response to greater peroxide production and greater oxidative stress as a result of feeding oxidized lipids. However, supplementing vitamin E in diets containing oxidized lipids has been shown to prevent and increase in GPx and reduce oxidative stress in broilers (Bayraktar et al., 2011).

Although significant negative correlations between serum TBARS with serum vitamin E, and significant positive correlations between serum TBARS with dietary TBARS concentration were observed, there were no correlations observed between serum vitamin E content and lipid oxidation conditions. Therefore, although biomarkers of oxidative stress were observed in some of these studies, their use as predictors of subsequent growth performance when feeding oxidized lipids is limited.

Table 2. *Summary of effects from feeding isocaloric diets containing dietary oxidized lipids on oxidative status of broilers and pigs (adapted from Hung et al., 2017)*

Measure	No. observations	Response to dietary oxidized lipids				
		Increase	Decrease	No change	Not reported	Unknown
Vitamin E[1]	65	0	17	5	43	0
TBARS[2]	65	4	0	13	44	4
GPx activity[3]	65	2	1	4	58	0

[1]Serum, plasma, or tissue concentrations of α-tocopherol.
[2]Serum, plasma, or tissue concentrations of thiobarbituric acid reactive substances.
[3]Liver and plasma glutathione peroxidase (GPx) activity.

An increase in liver weight relative to body weight is one of the most consistent indicators of oxidative stress from feeding oxidized lipids (Juberg et al., 2006; Liu et al., 2014c; Eder, 1999; Huang et al., 1988). This response may be a result of increased synthesis of microsomal enzymes in response to alleviating toxicity (Huang et al., 1988). However, use of this indicator to predict animal growth responses from feeding oxidized lipids is not practical.

Changes in intestinal barrier function are another indicator of oxidative stress that may be influenced by feeding oxidized lipids. Intestinal epithelial cells contain relatively high amount of polyunsaturated fatty acids which provide intestinal epithelial protection from pathogens (Willemsen et al., 2008), but long chain polyunsaturated fatty acids (PUFA) are susceptible to oxidation (Tappel, 1962). Therefore, oxidation of PUFA in intestinal epithelial cell membranes can lead to cell injury and impair epithelial

barrier function as a result of disruption of normal membrane structure and function (Lauridsen et al., 1999). Studies have shown that feeding oxidized lipids causes metabolic stress in intestinal enterocytes (Ringsies et al., 2007; Reddy and Tappel, 1974), and the longevity of enterocytes was reduced in broilers fed diets containing oxidized lipids (Dibner et al., 1996). However, feeding oxidized corn oil, canola oil, beef tallow, or poultry fat had no effect on intestinal barrier function of weaned pigs (Liu et al., 2014c).

EFFECTS OF FEEDING OXIDIZED LIPIDS ON OXIDATION OF POULTRY MEAT AND BENEFITS OF DIETARY ANTIOXIDANT SUPPLEMENTATION

Although many factors such as pre-slaughter stress, aging, processing, and storage conditions affect lipid and protein oxidation of poultry meat (Min and Ahn, 2005), diet can also play an important role. Feeding oxidized lipids has been shown to induce oxidative stress in poultry (Estévez, 2015). Feeding oxidized vegetable oil has been shown to increase malondialdehyde (MDA) concentrations in plasma, and reduce liver antioxidant activity of chickens compared with feeding unoxidized oil (Engberg et al., 1996). Zhang et al. (2011) showed that feeding oxidized oil to broilers resulted in increased oxidative stress in blood as well as increased lipid and protein oxidation in breast muscle compared with birds fed unoxidized oil. Similarly, Delles et al. (2014) showed an increase in lipid oxidation in serum, and increased lipid and protein oxidation in muscle in birds fed oxidized oil.

Results from several studies have shown that the concentration of polyunsaturated fatty acids in poultry muscle tissues can be accomplished by modifying the dietary fatty acid composition and supplementation with α-tocopherol (200 mg/kg) and ascorbate (1,000 mg/kg) independently or in combination with trace minerals with antioxidant properties such as selenium, zinc, and magnesium (Estévez, 2015). Furthermore, dietary supplementation with several feed additives containing high concentrations of phenolic acid compounds have been shown to be effective in minimizing lipid and protein oxidation in fresh and processed poultry meat products (Estévez, 2015). Addition of phenolic-rich compounds to broiler diets have also been shown to have potential human health benefits when consuming meat products (Lund et al., 2011).

SUMMARY

There have been numerous studies conducted to evaluate the effects of feeding various oxidized lipids on broiler and pig growth performance. Although responses have been inconsistent, sufficient evidence has been reported to indicate that growth rate is often reduced as a result of decreased feed intake independent of caloric intake. This is likely due to the toxic effects of lipid oxidation products consumed when feeding oxidized lipids to pigs and broilers. A reduction in serum or plasma vitamin E concentration, and an increase in serum TBARS as well as an increase in liver weight relative to live body weight are good indicators of oxidative stress caused by feeding oxidized lipids. There is also some evidence that dietary oxidized lipids may reduce gut health by impairing gut barrier function in the small intestine. Because of the complexity of the lipid oxidation process, the multiple oxidation products that are produced and degraded over time, and the specificity of oxidation products measured with various indicator assays, our ability to use these oxidation indicator test to accurately predict reductions in animal growth performance is limited. As a result, using a single measurement of lipid oxidation is insufficient for predicting animal growth performance. Therefore, minimizing these negative growth performance and health effects can be accomplished by using high quality, minimally oxidized fats and oils, such as degummed U.S. soybean oil, and protecting these lipids from further oxidation with the use of antioxidants. Finally, min-

imizing dietary lipid oxidation, supplementing broiler diets with α-tocopherol and ascorbate, and using of feed additives containing high concentrations of phenolic compounds have been shown to be effective in minimizing lipid and protein oxidation in poultry meat.

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Chapter

05

Effects of Feeding Oxidized Soybean Oil and Dietary Antioxidants to Swine

INTRODUCTION

Lipid oxidation is a complex process that begins with increasing peroxide production during the initiation phase, which are subsequently degraded into aldehydes and acids during the propagation phase, and further degradation leads to the production of polar compounds and indigestible polymers during the termination phase during extended thermal exposure (St. Angelo et al., 1996; Gonzalez-Muñoz et al., 1998). As a result, multiple indicator measures representing the various stages of lipid oxidation should be used when assessing lipid quality.

Soybean oil contains a high proportion of polyunsaturated fatty acids which makes it highly susceptible to oxidation when exposed to heat, oxygen, light, and transition metals, which often occurs during transport and storage. However, compared to other feed fats and oils, soybean oil also contains relatively high concentrations of natural antioxidants such as tocopherols, tocotrienols, and carotenoids, which provide some protection against oxidation compared with other lipids. Until recently, there has been very little published information about the extent of soybean oil oxidation when exposed to different thermal treatments, and its effects on energy content, growth performance, and intestinal health of growing pigs. Therefore, the information provided in this chapter may provide some useful information about the extent of oxidation and subsequent effects from feeding oxidized soybean oil from various thermal treatment conditions.

CHEMICAL COMPOSITION OF THERMALLY OXIDIZED SOYBEAN OIL

Lindblom et al. (2018) compared the chemical composition of fresh, unoxidized U.S. soybean oil to soybean oil oxidized under 3 conditions: 1) heated at 45°C for 288 hours; 2) heated at 90°C for 72 hours; and 3) heated at 180°C for 6 hours, with all treatments exposed to air at a rate of 15L/minute. No antioxidants were added before or after heating. These thermal treatments were chosen to simulate conditions of feed in a bulk bin during summer months (45°C), approaching temperatures (90°C) for rendered animal fat processing (115 to 145°C; Meeker and Hamilton, 2006), and frying temperature (180°C) for frying foods in the restaurant industry. Fatty acid composition of soybean oil subjected to these 4 thermal treatments is shown in **Table 1,** and the concentrations of lipid oxidation products and quality indicators are shown in **Table 2.** The slight decrease in linoleic and linolenic acid content, and unsaturated to saturated fatty acid ratio (U:S) was expected for the higher temperature treatments because longer chain unsaturated fatty acids are more susceptible to oxidation than fatty acids with shorter chain lengths and unsaturated fatty acids. However, these concentrations were only reduced for the 90°C for 72 hours treatment, and were minimally affected by the heat treatment of 180°C for 6 hours **(Table 1).**

Free fatty acid (FFA) content is usually increased after lipids are exposed to heat, but FFA content did not change substantially with increased temperatures used in this study **(Table 2).** However, peroxide value increased when oils were heated at 45°C for 288 hours, and further increased when heated at 90°C for 72 hours, but then declined to a low concentration when oil was heated at 180°C for 6 hours **(Table 2).** This suggests that initial peroxide products were degraded and began forming secondary and tertiary oxidation compounds in the oil heated at 180°C for 6 hours. Compared with thiobarbituric acid reactive substances (TBARS), which changed very little with increasing thermal treatment, anisidine value, which is a unit-less measure of high molecular weight aldehydes, was found in the highest concentrations in oils heated at 90°C and 180°C. All of the aldehydes were dramatically increased in oils heated at 90°C and 180°C, as well as were the polymerized triacylglycerides. Although total tocopherol content declined among the 3 thermal treatments, the amount of loss was not as great as may have been expected. These results show that substantial oxidation of soybean oil occurs at temperatures of 90°C and 180°C.

Table 1. *Fatty acid profile of thermally processed soybean oil (adapted from Lindblom et al., 2018)*

Heating temperature, °C	22.5	45	90	180
Heating time, hours	0	288	72	6
Fatty acids, % of total lipid				
C14:0 (myristic)	0.08	0.07	0.09	0.08
C16:0 (palmitic)	10.80	10.94	12.25	11.26
C16:1 (palmitoleic)	ND	0.08	0.09	ND
C17:0 (margaric)	0.11	0.10	0.12	0.11
C18:0 (stearic)	3.83	3.88	4.35	4.03
C18:1 (oleic)	22.08	22.29	24.28	22.78
C18:2 (linoleic)	54.05	53.74	50.96	53.02
C18:3 (linolenic)	7.83	7.50	6.27	7.07
C19:0 (nonadecanoic)	0.24	0.27	0.20	0.39
C20:0 (arachidic)	0.30	0.31	0.34	0.32
C20:1 (gadoleic)	0.18	0.19	0.21	0.30
C22:0 (behenic)	0.36	0.35	0.23	0.38
C22:5 (docosapentaenoic)	ND	0.11	0.12	ND
Other fatty acids	0.13	0.15	0.35	0.20
Unsaturated:saturated	5.35	5.27	4.64	5.02
Iodine value[1]	133	132	126	130

[1]Iodine value was calculated according to Meadus et al. (2010).

Table 2. *Concentrations of oxidation indicators and other quality measures of thermally processed soybean oil (adapted from Lindblom et al., 2018)*

Heating temperature, °C	22.5	45	90	180
Heating time, hours	0	288	72	6
Free fatty acids, %	0.04	0.07	0.35	0.14
Moisture, %	0.02	0.02	0.10	0.02
Insoluble impurities, %	0.02	0.02	0.04	0.02
Unsaponifiable matter, %	0.29	0.35	0.53	0.30
Oxidized fatty acids, %	1.3	2.5	3.1	1.4
OSI at 110°C, hours	7.15	3.65	2.70	3.35
p-Anisidine value[1]	1.19	8.38	261	174
Peroxide value, mEq/kg	2.0	95.6	145	4.0
Total polar compounds, %	2.67	7.01	22.65	10.19
Polymerized triacylglycerides, %	ND	ND	6.39	2.06
Thiobarbituric acid value[1]	0.10	0.14	0.14	0.09
Aldehydes, mg/kg				
2,4-decadienal	2.11	5.50	548	324
4-hydroxynonenal	0.05	1.05	39.46	25.71
Acrolein	3.88	3.31	15.82	45.39
Decenal	0.24	0.35	28.17	19.81
Heptadienal	0.12	4.40	85.50	61.86

Continuation Table 2. *Concentrations of oxidation indicators and other quality measures of thermally processed soybean oil (adapted from Lindblom et al., 2018)*

Heating temperature, °C	22.5	45	90	180
Heating time, hours	0	288	72	6
Heptanal	0.22	3.60	89.12	40.08
Hexanal	2.97	2.71	21.20	16.84
Octenal	0.19	1.10	59.86	21.31
Pentanal	0.28	0.31	1.82	2.50
Undecadienal	0.10	0.18	26.02	15.35
Undecenal	0.27	0.29	27.57	23.38
Aldehyde ratio[2]	0.16	0.14	0.64	0.57
Total tocopherols[3], mg/kg	772	620	405	609

[1]There are no units for p-anisidine value or thiobarbituric acid values.
[2]Ration of 2-decenal, 2,4-hydroxynonenal, 2,4-undecadienal, and 2-undecenal as a percentage of total aldehydes to acrolein, 2,4-heptadienal, and 2-heptenal as a percentage of total aldehydes (Wang et al., 2016).
[3]Total tocopherols included alpha, beta, delta, and gamma tocopherols.

ENERGY, LIPID, AND NITROGEN DIGESTIBILITY IN GROWING PIGS FED THERMALLY OXIDIZED SOYBEAN OIL

Growing barrows (25 kg initial body weight) were fed diets containing 10% of the 4 different thermally processed soybean oils to determine energy, lipid, and nitrogen digestibility, nitrogen retention and intestinal permeability (Lindblom et al., 2018; **Table 3**). Pigs fed the 90 °C thermally processed soybean oil had the lowest digestible energy (DE) as a percentage of gross energy (GE), while the metabolizable energy (ME) as a percentage of DE was lowest in pigs fed the soybean oil processed at 180 °C, followed by the 90 °C, 45 °C, and unoxidized oil treatments, respectively. Similarly, pigs fed 90 °C thermally processed soybean oil had the lowest lipid digestibility, followed by pigs fed 180 °C, 45 °C, and fresh soybean oil treatments, respectively. Nitrogen digestibility tended to be greater when feeding fresh soybean oil compared with feeding the heat processed oil at 45 °C, but was not different for the higher temperature soybean oil processing treatments. This resulted in greater percentage of nitrogen retained in pigs fed fresh soybean oil followed by pigs fed 45 °C, 180 °C, and 90 °C soybean oil treatments, respectively. However, no differences were observed among soybean oil thermal processing treatments for urinary lactulose to mannitol ratio, which is a commonly used indicator of intestinal permeability and intestinal health. Overall, thermal processing of soybean oil at different times and temperatures had minimal effects on energy, lipid, and nitrogen digestibility, and had no effect on intestinal permeability of growing pigs. Unfortunately, although significant correlations were observed between various soybean oil quality indices and energy and nutrient digestibility responses, they were relatively low (r = -0.24 to -0.51). Peroxide value had the greatest negative correlation with DE:GE (r = -0.40), polymerized triacylglycerides had the greatest negative correlation with lipid digestibility (r = -0.51), and anisidine value, hexanal, and 4-hydroxynonenal had the greatest negative correlations (r = -0.43) with nitrogen retention. Therefore, our ability to energy and nutrient digestibility responses of pigs fed oxidized soybean oil using various indicators of oxidation is poor.

Table 3. *Energy, lipid, and nitrogen digestibility, nitrogen retention and intestinal permeability of pigs fed diets containing 10% thermally oxidized soybean oil (adapted from Lindblom et al., 2018)*

Heating temperature, °C	22.5	45	90	180
Digestible energy as % of gross energy	88.6^{a}	87.8^{bc}	87.3^{c}	88.4^{ab}
Metabolizable energy as % of digestible energy	99.2^{a}	99.0^{ab}	98.8^{b}	98.6^{b}
Lipid digestibility, %	83.0^{a}	82.1^{ab}	78.4^{c}	81.2^{b}
Nitrogen digestibility, %	88.7^{x}	87.1^{y}	88.2^{xy}	88.7^{x}
Nitrogen retained, %	90.6^{a}	89.0^{ab}	86.1^{c}	86.9^{b}
Urinary lactulose:mannitol	0.05	0.06	0.05	0.04

^{a,b,c}Means with uncommon superscripts are different (P < 0.05).
^{x,y}Means with uncommon superscripts are different (P < 0.10).

GROWTH PERFORMANCE OF PIGS FED THERMALLY OXIDIZED SOYBEAN OIL

When these diets were fed to barrows from 25 to 71 kg body weight, average daily gain (ADG) was similar among pigs fed soybean oil processed at 22.5 °C, 45 °C, and 180 °C, which were greater than pigs fed the 90 °C thermally processed soybean oil diet (Lindblom et al., 2018; **Table 4**). These results are in agreement with the high amount of oxidation products for this oil source **(Table 2),** and the reduced energy and lipid digestibility and nitrogen retained **(Table 3).** However, it was somewhat surprising that feeding the soybean oil source thermally oxidized at 180 °C had no effect on ADG even though it had the second greatest amount of oxidation products compared with the soybean oil source heated at 90 °C. Feeding oxidized lipids typically reduces average daily feed intake (ADFI; Hung et al., 2017), but there were no differences among oxidized soybean oil treatments in this study. Furthermore, feeding oxidized lipids to pigs generally results in reductions in Gain:Feed (G:F; Hung et al., 2017), but there were no differences among treatments, except that feeding the 45 °C heated soybean oil resulted in greater G:F compared with other treatments. Similar to energy and nutrient digestibility correlations, significant correlations were observed between various soybean oil quality indices and growth performance traits, but they were relatively low (r = -0.26 to -0.47). Polymerized triacylglycerides had the greatest correlation with ADG (r = - 0.47), peroxide value and oxidized fatty acids were the only quality indicators correlated with ADFI (r = -0.28), and the aldehyde ratio had the highest correlation (r = -0.35) with G:F responses. Therefore, our ability to predict growth performance responses of pigs fed oxidized soybean oil using various indicators of oxidation is poor.

Table 4. *Comparison of growth performance from pigs fed soybean oil with different oxidation levels from 25 to 71 kg body weight (adapted from Lindblom et al., 2018)*

Heating temperature, °C	22.5	45	90	180
ADG, kg	1.02^{a}	1.05^{a}	0.96^{b}	1.03^{a}
ADFI, kg	2.05	2.00	1.94	2.09
G:F	0.50^{b}	0.53^{a}	0.49^{b}	0.50^{b}

^{a,b}Means with uncommon superscripts are different (P < 0.05).

CARCASS CHARACTERISTICS, LOIN QUALITY, AND SHELF LIFE OF LOIN CHOPS FROM PIGS FED THERMALLY OXIDIZED SOYBEAN OIL

A subsequent study was conducted by Overholt et al. (2018a, 2018b) to determine the effects of soybean oil compositional changes and oxidation indices from the same time and temperature treatments used by Lindblom et al. (2018). No antioxidants were added before or after heating. These oils were added at an inclusion level of 10% to corn-soybean meal diets to determine energy and nutrient digestibility, growth performance, and effects on carcass characteristics, loin quality, and shelf life of loin chops. Changes in soybean oil chemical composition and oxidation indicators were similar to those reported by Lindblom et al. (2018). Results for energy and nutrient digestibility were slightly different than those reported by Lindblom et al. (2018), where feeding diets containing fresh soybean oil resulted in the greatest DE:GE (91.13%), with the 45 °C thermally processed soybean oil being intermediate (90.96%), and pigs fed the 90 °C and 180 °C heat treated soybean oil having the lowest DE:GE (89.51% and 89.37%, respectively). However, there were no differences in ME:DE among the thermally processed soybean oil treatments. Differences in lipid digestibility among soybean oil treatments followed that same pattern as for DE:GE, but there were no differences in nitrogen digestibility, nitrogen retention, or intestinal permeability among treatments. Overall growth performance (81-day feeding period; initial body weight = 47 kg, final body weight = 131 kg) responses of pigs were similar to those reported by Lindblom et al. (2018) where there were no differences among treatments for ADFI, but pigs fed the 90 °C thermally treated soybean oil had reduced ADG and G:F compared with the other treatments. Pigs were slaughtered on day 82 of this trial, and carcasses were collected for further evaluation.

As a result of reduced ADG from feeding diets containing the 90 °C oxidized soybean oil, live body weight at slaughter, dressing percentage, and hot carcass weight were also reduced compared with feeding the other thermally processed soybean oil treatments **(Table 5).** Liver weight, and liver weight as a percentage of live weight, were increased by feeding 90 °C and 180 °C soybean oil diets. Increased liver weight is commonly observed in pigs fed oxidized lipids (Liu et al., 2014; Liu, 2015), and is an indication of oxidative stress. This occurs because the liver is the primary organ involved in detoxification in the body, which increases microsomal enzymes (Huang et al., 1988), and hepatocyte proliferation occurs (Dibner et al., 1996) after prolonged consumption of toxins, such as 4-hydroxynonenal (Esterbauer et al., 1991; Grootveld et al., 1998). Concentrations of 4-hydroxynonenal were much greater in soybean oils heated at 90 °C and 180 °C, than oils in the other two treatments. However, thermal treatments of soybean oil had no effect on 10th rib backfat thickness, loin muscle area, and estimated percentage of carcass lean.

Table 5. *Carcass characteristics of fresh bellies from barrows fed soybean oil with different oxidation levels from 47 to 131 kg body weight (adapted from Overholt et al., 2018b)*

Heating temperature, °C	22.5	45	90	180
Live weight at slaughter, kg	127.2^{ab}	130.5^{a}	121.6^{b}	129.2^{a}
Lairage weight loss, %	3.06	3.20	3.27	3.32
Hot carcass weight, kg	101.8^{a}	104.4^{a}	95.8^{b}	102.7^{a}
Dressing percentage, %	80.0^{a}	90.0^{a}	78.7^{b}	79.5^{a}
Liver weight, kg	1.54^{b}	1.66^{ab}	1.76^{a}	1.72^{a}
Liver weight as percentage of live weight, %	1.21^{c}	1.27^{bc}	1.45^{a}	1.33^{b}
10th rib backfat depth, cm	2.65	2.55	2.29	2.54
Loin muscle area, cm^2	52.5	53.0	48.5	51.4
Estimated carcass lean, %	51.1	51.5	52.1	51.3

^{a,b,c}**Means with uncommon superscripts are different (P < 0.05).**

Previous studies have reported an increased rate of lipid oxidation in pork loin chops when derived from pigs fed oxidized corn oil compared with feeding unoxidized corn oil (Buckley et al., 1989; Monahan et al., 1992). However, in this study, there were no effects of feeding the oxidized soybean oil treatments on loin pH at 24 hours post-mortem, lightness (L*), redness (a*), yellowness (b*), marbling and firmness scores, drip loss, moisture content, or extractable lipid content among treatments. Discoloration of loins and malondialdehyde content of tissue increased during the 10-day storage period (data not shown), but heated soybean oil treatments had no effect. Similar to results reported by Monahan et al. (1994) and Boler et al. (2012) from feeding oxidized corn oil, the reduction in vitamin E content of soybean oil after heat treatment was apparently not sufficient to adversely affect color stability and lipid oxidation in loin chops in this study.

Table 6. *Fresh loin characteristics from barrows fed soybean oil with different oxidation levels from 47 to 131 kg body weight (adapted from Overholt et al., 2018b)*

Heating temperature, °C	22.5	45	90	180
24 hour pH	5.46	5.44	5.48	5.43
L*	49.6	49.8	50.6	49.9
a*	7.60	8.48	7.96	7.82
b*	0.35	0.48	0.85	0.80
NPPC color	2.23	3.33	5.47	5.19
NPPC marbling	1.00	1.21	1.14	1.07
NPPC firmness	2.00	2.14	1.79	1.57
Drip loss, %	2.70	3.18	2.92	3.55
Moisture, %	74.1	74.2	74.1	74.4
Extractable lipid, %	3.36	3.20	3.28	2.93

[1]Color measurements determined using Minolta CR-400 Chroma-meter
[2]NPPC (1999).
[3]NPPC (1991).

PROCESSING CHARACTERISTICS AND SHELF LIFE OF BACON FROM PIGS FED THERMALLY OXIDIZED SOYBEAN OIL

Bellies from pigs fed diets containing the same thermally processed soybean oils in the Overholt et al. (2018a, 2018b) studies were also evaluated for differences in quality and shelf life stability of fresh bellies as well as commercially processed bacon under retail storage conditions. Pigs were slaughtered on day 82 of this trial, and bellies were collected for further evaluation (Overholt et al., 2018c). There were no differences among oxidized soybean oil treatments for fresh belly weight, length, width, and thickness (Table 7). However, the flop distance of fresh bellies from pigs fed the 90 °C processed soybean oil was greater than that of bellies from other treatments, indicating greater belly firmness. This response is consistent with the lower iodine value (IV) of bellies from pigs fed the 90 °C processed soybean oil, compared to those fed the 22.5 °C and 45 °C processed soybean oil, and less than the 180 °C processed soybean oil treatments. These differences in belly IVs were expected because of the lower slightly lower IVs of soybean oils processed at 90 °C (IV = 126) and 180 °C (IV = 127), compared with those processed at 22.5 °C (IV = 131) and 45 °C (IV = 131). However, these results were unexpected because the energy digestibility of the diets containing 90 °C and 180 °C heated processed soybean oil was less than fresh soybean oil and soybean oil heated at 45 °C.

There were no differences in initial, injected, cooked, or sliced weight, or sliced yield, moisture, and extractable lipid content of bacon among dietary treatments **(Table 8).** The only difference observed was a reduction in brine injection uptake of bellies from pigs fed the heat processed soybean oil at 90 °C, compared to the other dietary treatments. Because of differences in IV of the different heat processed soybean oil treatments, it was expected that there may be differences in bacon slicing yield, which did not occur.

Table 7. *Characteristics of fresh bellies from barrows fed soybean oil with different oxidation levels from 47 to 131 kg body weight (adapted from Overholt et al., 2018c)*

Heating temperature, °C	22.5	45	90	180
Belly weight, kg	7.41	7.46	7.24	7.61
Flop distance, cm	6.37[b]	6.51[b]	8.07[a]	6.21[b]
Length, cm	69.6	70.6	70.7	70.6
Width, cm	28.4	28.5	27.4	28.7
Thickness, cm	3.67	3.87	3.82	3.64
Iodine value				
Whole core	92.9[a]	93.2[a]	79.7[c]	89.9[b]
Middle and inner layer	95.6[a]	94.9[a]	82.9[c]	91.7[b]
Outer layer	93.2[a]	94.0[a]	80.1[c]	90.6[b]

[a,b,c]**Means with uncommon superscripts are different (P < 0.05).**

Table 8. *Characteristics of commercially manufactured bacon from barrows fed soybean oil with different oxidation levels from 47 to 131 kg body weight (adapted from Overholt et al., 2018c)*

Heating temperature, °C	22.5	45	90	180
Initial weight, kg	5.80	5.78	5.59	5.88
Injected weight, kg	6.88	6.87	6.57	6.99
Injection uptake, %	18.8a	18.7a	17.4b	18.6a
Cooked weight, kg	6.22	6.23	5.98	6.28
Cooked yield, %	107.2	107.6	106.7	106.4
Sliced weight, kg	3.38	4.11	4.00	3.88
Sliced yield (green weight), %	59.1	71.4	71.5	67.0
Sliced yield (cooked weight), %	55.2	66.4	67.0	63.1
Moisture, %	41.3	46.0	44.8	45.5
Extractable lipid, %	42.6	39.6	39.2	39.1

[a,b,c]**Means with uncommon superscripts are different (P < 0.05).**

Commercially processed bacon was stored and analyzed for TBARS concentration in tissue and extractable lipid, as well as the presence of oxidized odor and flavor by trained panelists on day 0, 30, 60, and 90 of storage at -20 °C. Although length of storage time increased TBARS content and oxidized odor and flavor of bacon, feeding diets containing different thermally processed soybean oils had no effect on these measures. These results suggest that feeding oxidized soybean oil did not affect the quality of fresh bellies or quality, shelf life, and slicing yields of bacon.

EFFECTS OF ADDING ANTIOXIDANTS TO SWINE DIETS CONTAINING OXIDIZED SOYBEAN OIL ON GROWTH PERFORMANCE, CARCASS CHARACTERISTICS, AND OXIDATIVE STATUS

Although the addition of antioxidants to oxidized lipid diets may be beneficial for alleviating oxidative stress and growth performance reductions in pigs, only a limited number of studies have been conducted to evaluate these effects (Chang and van Heugten, 2016; Lu et al., 2014a; Hung et al., 2019). Hung et al. (2019) evaluated the effects of adding a commercially available antioxidant (TBHQ) to moderately oxi-

dized corn oil in diets on growth performance and oxidation status in nursery pigs. The moderately oxidized corn oil contained 5.98 mEq O_2/kg and TBARS of 0.11 mg malondialdehyde (MDA) equivalent/g of oil. The addition of TBHQ to diets containing oxidized corn oil resulted in a 37% reduction in peroxide value and increased the oil stability index by 69%, but feeding the oxidized corn oil diets had no effects on growth performance. However, feeding diets containing oxidized oil tended to increase the hepatosomatic index (increase liver weight relative to body weight) by 5% and reduced serum vitamin E concentrations. The addition of TBHQ to oxidized corn oil was not effective in alleviating these effects. These results are consistent with those reported by Chang and van Heugten (2016) who observed no differences in growth performance of nursery pigs fed diets containing oxidized corn oil containing 60 mg/kg of an antioxidant blend of ethoxyquin, butylated hydroxytoluene (BHT), and butylated hydroxyanisole (BHA). However, Lu et al. (2014a) added 135 mg/kg of an antioxidant blend of ethoxyquin and propyl gallate to oxidized soybean oil diets and observed improvements in growth performance comparable to feeding a corn-soybean meal diet containing no antioxidants.

Lu et al. (2014a) evaluated the effectiveness of adding a commercial antioxidant blend (135 mg/kg of AGRADO PLUS®; ethoxyquin and propyl gallate) or 11 IU/kg of additional vitamin E (total of 24 IU/kg vitamin E) to nursery, grower, and finisher diets (5 phases) containing 5% oxidized soybean oil (peroxide value = 180 mEq/kg of oil) and 10% of a commercial polyunsaturated fatty acid (PUFA) source (55% crude fat, 36% docosahexaonic acid) on growth performance, liver function, and oxidative status of pigs during an 118-day wean to finish feeding period. In this study, pigs fed the oxidized soybean oil without supplemental vitamin E and antioxidant were switched to the control diets on day 83 of the feeding period because the pigs were exhibiting signs of very poor health. Feeding the oxidized soybean oil diets, with or without additional supplemental vitamin E (11 IU/kg), was not effective in minimizing the adverse effects on growth performance and oxidative stress **(Table 9).** However, adding the synthetic antioxidant to the oxidized soybean oil diets was effective in restoring growth rate and improving gain efficiency, even though feed intake was not completely restored, compared to pigs fed the unoxidized soybean oil control diet.

Feeding the oxidized soybean oil diets resulted in a greater liver to live body weight ratio, which was reduced by adding the combination of supplemental vitamin E and synthetic antioxidant, or addition of the synthetic antioxidant alone, compared with feeding the unoxidized soybean oil diet (data not shown).

Bilirubin is an end product of red blood cell turnover, and can be used as an indicator of erythrocyte hemolysis resulting from damage caused by free radicals and other oxidation products. Bilirubin concentrations were non-detectable in plasma from pigs fed the control diet, but was increased in pigs fed the oxidized soybean oil diet, which was subsequently reduced by adding the synthetic antioxidant.

Similarly, increased concentrations of liver function enzymes (alanine transaminase and aspartate transaminase) can be used as indicators of liver damage because they serve as biomarkers of liver function. There were no differences among dietary treatments for plasma alanine transaminase, but the increase in aspartate transaminase concentrations in pigs fed the oxidized soybean oil diet is indicative of oxidative stress which may be potentially due to hepatocellular necrosis. This effect was partially alleviated by adding the synthetic antioxidant to the diet.

The concentration of plasma TBARS is a common biomarker for assessing free-radical induced damage and endogenous lipid oxidation, and plasma carbonyl concentration is an indicator of oxidative damage of proteins and amino acids. In this study, both TBARS and carbonyl concentrations in plasma were in-

creased by feeding oxidized soybean oil diets, but adding the synthetic antioxidant restored plasma levels comparable to those in pigs fed the control unoxidized soybean oil diet.

In summary, this is the first study to show that adding a specific commercial antioxidant blend, with or without supplemental vitamin E (11 IU/kg), to diets containing 5% oxidized soybean oil was effective in improving growth performance, liver function, and reducing plasma biomarkers indicative of oxidative stress. Furthermore, feeding the oxidized soybean oil diets caused changes in carcass characteristics and meat quality, which were partially alleviated with the addition of the synthetic antioxidant, while adding 11 IU/kg of supplemental vitamin E had minimal effects (Lu et al., 2014b).

Table 9. *Effects of feeding diets containing 5% oxidized soybean oil, with or without additional supplemental vitamin E (11 IU/kg) or synthetic antioxidant (AGRADO PLUS®), on growth performance and indicators of oxidative stress (adapted from Lu et al., 2014)*

Measure	Dietary Treatment[1]				
	Control unoxidized SO	Oxidized SO + PUFA	Oxidized SO + PUFA + VE	Oxidized SO + PUFA + AOX	Oxidized SO + PUFA + VE + AOX
Growth performance					
ADG, kg	1.05[a]	0.61[b]	0.70[b]	0.99[a]	1.01[a]
ADFI, kg	2.81[a]	1.67[c]	1.66[c]	2.25[b]	2.34[b]
G:F	0.38[bc]	0.37[c]	0.42[ab]	0.44[a]	0.43[a]
Plasma oxidation biomarkers					
Y-glutamyl transpeptidase, IU/L	10.18	11.35	17.60	18.56	18.28
Total bilirubin, mg/dL	ND[2b]	0.30[ab]	1.67[a]	0.84[ab]	ND[b]
Alanine transaminase, U/L	30.26	23.25	30.52	21.65	24.11
Aspartate transaminase, IU/L	21.55[b]	22.66[b]	36.34[a]	21.32[b]	21.35[b]
TBARS, µM/mL	2.33[b]	2.76[b]	10.56[a]	4.21[b]	4.10[b]
Carbonyl, nmol/mL	19.24[b]	25.94[b]	71.53[a]	24.21[b]	21.31[b]

[1]SO = soybean oil; PUFA = 10% commercial PUFA sources providing 2.05% docosahexaenoic acid to the diet; VE = vitamin E supplemented at 11 IU/kg of diet to provide a total of 24 IU/kg of diet; AOX = commercial synthetic antioxidant (AGRADO PLUS; Novus International, Inc.)
[2]ND = not detectable.
[a,b,c]Means with uncommon superscripts within row are different (P < 0.05).

It is important to recognize that in the U.S., the Food and Drug Administration regulates the use of synthetic antioxidants in foods and animal feeds. Currently, the maximum diet inclusion levels of ethoxyquin, BHA, and BHT are 0.02% of lipid content, 150 mg/kg, and 200 mg/kg, respectively (Salami et al., 2016). These restrictions are due to feed safety concerns because if they exceed these dosage rates, these antioxidants are degraded into metabolites that have been shown to be cytotoxic (Okubo et al., 2003) and can cause DNA damage (Shahidi and Zhong, 2005). Furthermore, excessive use of antioxidants can result in oxidative stress (Poljsak et al., 2013) resulting from an oxidant-antioxidant imbalance (Salami et al., 2016; Poljsak and Milisav, 2012). Therefore, following manufacturer recommendations for the addition of synthetic antioxidants to animal feed is essential to avoid the potential deleterious effects.

SUMMARY

Soybean oil exposed to 90 °C for 72 hours and 180 °C for 6 hours significantly increased oxidation and production of aldehydes compared with fresh soybean oil and oil thermally processed at 45 °C. Increased liver weights in pigs fed soybean oil heated a 90 °C for 72 hours and 180 °C for 6 hours increased liver weights, which is indicative of oxidative stress, but thermal treatment of soybean oil had no effect on intestinal permeability. Except for feeding diets containing 10% soybean oil heated at 90 °C for 72 hours,

there were minimal effects on energy, lipid, and nitrogen digestibility, growth performance, carcass characteristics, loin and bacon quality and shelf life stability. These results suggest that feeding oxidized soybean oil can have deleterious effects on pig performance, but these effects are dependent on the temperature and time conditions used to create oxidation products. Very few studies have been conducted to evaluate the effects of feeding supplemental vitamin E or commercially available synthetic antioxidants in diets containing oxidized soybean oil. However, there is some evidence that adding a specific commercial antioxidant blend, with or without supplemental vitamin E (11 IU/kg), to diets containing 5% oxidized soybean oil may be effective in improving growth performance, liver function, reducing plasma biomarkers indicative of oxidative stress, carcass characteristics and meat quality However, low supplemental levels of vitamin E had minimal effects on alleviating the adverse effects of feeding oxidized soybean oil.

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Chapter

06

Protecting the Quality of U.S. Soybean Oil

INTRODUCTION

Precision animal nutrition not only involves selecting and using feed ingredients that contain high concentrations of energy and digestible nutrients, but also preserving high nutritional value during processing, transport, storage, and feed manufacturing. One of the goals in precision nutrition is to manage variability in energy and nutrient composition of feed ingredients to obtain predictable results. This is especially important when using high quality oils, such as U.S. degummed soybean oil, in swine and poultry diets in climates with high temperatures and relative humidity because of its susceptibility to oxidative damage when exposed to high temperatures, sunlight, oxygen (air and moisture), and transition metals. Although soybean oil is superior to other fats and oils for its high energy value, it is inferior in its thermal stability when exposed to high temperatures. Oil oxidation occurs through an autocatalytic reaction that produces hydroperoxides from unsaturated Acylglycerols, and causes unpleasant taste and odors, degradation of functional and nutritional properties, as well as reduced shelf life. In addition, oxidation causes numerous chemical changes of oils, including production of free radicals that may cause irreversible damage when reacting with DNA, proteins, and lipids (Bansal et al., 2010; Cabiscol et al., 2010). Therefore, the effects of lipid oxidation are irreversible after it occurs, even with the addition of antioxidants. Therefore, designing handling and storage systems that minimize oxidative damage are essential for capturing the most nutritional value for feed fats and oils. Unfortunately, most importers and feed mills provide little attention to the importance of minimizing oxidation of feed fats and oils and preventing further oxidation before adding these expensive ingredients to animal feeds. The purpose of this chapter is to describe recommended transport, storage, and handling procedures to minimize oxidative damage to soybean oil.

Table 1. *Effects of thermal exposure (60 °C) and time on oxidation of soybean oil (adapted from Li et al., 2014)*

Time, days	Peroxide value, mEq O_2/kg oil	p-Anisidine value
0	2.34	4.75
4	7.93	7.71
8	13.7	10.8
12	17.5	14.9
16	20.1	27.1
20	25.4	39.1
24	28.3	44.1

KNOW YOUR SOYBEAN OIL SOURCE AND HOW IT IS MANAGED FROM PRODUCTION UNTIL DELIVERY

Develop a questionnaire from your prospective suppliers to determine length of time, temperature, and relative humidity conditions that the soybean oil has been exposed. Information should also include initial peroxide value, TBARS, and p-anisidine value of the product you are receiving. Although most suppliers provide peroxide values, free fatty acid content, and MIU's for each shipment based on minimum or maximum guarantees for trading specifications, a measure of aldehyde concentrations (TBARS or p-anisidine value) should also be provided to more accurately characterize the extent of oxidation.

For example, Li et al. (2014) showed that the peroxide value and p-anisidine value of soybean oil exposed to 60 °C increases during extended storage periods **(Table 1).** Furthermore, the concentrations of conjugated dienes and trienes increased over time (data not shown). These thermal exposure conditions are likely to be similar to those used during transport and storage of soybean oil in hot humid climates, and indicate that preventative measures are need to preserve soybean oil quality.

Establishing quality benchmarks is essential for assessing the quality of fats and oils you are receiving and using over a given period of time. Analytical equipment for monitoring lipid quality can vary from simple photometric testers to more reliable reagent-based equipment and methods and more expensive Near InfraRed spectroscopy (NIR). In general, although they are more expensive, using chemical assays provides more reliable and meaningful results compared with simpler, less expensive methods and equipment.

MINIMIZE AIR EXPOSURE

Air (oxygen) is a promoter of oxidation. The reaction rate between oxygen and lipids is dependent on the type of oxygen, where linoleic acid (most abundant fatty acid in soybean oil) reacts 1,450 times faster with $^1O_2$ than $^3O_2$ (Rawls and van Santen, 1970). Therefore, every attempt should be made to minimize air and oxygen exposure to minimize oxidation of soybean oil.

MINIMIZE LIGHT EXPOSURE

Lipid oxidation caused by $^1O_2$ occurs in the presence of sunlight, which indicates that the type of storage and packaging containers is very important. Transparent plastic bottles and IBC containers promote oil oxidation, but the use of Tinuvin 234 (2-(2-hydroxy-3,5-di(1,1-dimethylbenzyl)phenyl) benzotriazole) or Tinuvin 326 (2-(3'-tert-butyl-2'-hydroxy-5'-methylphenyl)-5-chlorobenzo-trazole), which are ultraviolet light absorbers into transparent plastic containers improves oxidative stability of soybean oil when exposed to light (Pascall et al., 1995; Azeredo et al., 2004). However, the preferred storage containers consist of stainless steel (types 302, 303, 316).

High-density polyethylene (HDPE) resin is extensively used as a packaging material because of its high tensile strength, hardness, and good chemical resistance. Blow-molded HDPE containers in the form used for bottles, jars, and jerry cans for packaging edible oils. Coltro et al. (2003) investigated the quality deterioration of soybean oil in 1 liter plastic bottles made of HDPE, and coextruded with a layer containing black pigment during a 113-day storage period at a temperature of 23°C. Results were compared with a control treatment where soybean oil was stored in a metal container during the same period of time and temperature. There were no differences observed for the organoleptic properties of the oil contained in the metal and plastic containers throughout the total storage time investigated, and the chemical quality of the oil remained within the limits of stability.

Surface area and surface tension of oil is of critical importance for minimizing oxidation. The free fatty acids of oils have hydrophilic ("water liking") carboxy groups in the chemical structures that do not easily dissolve in the hydrophobic ("water hating") portion of the oil mass, and are present on the surface of the oil. These free fatty acids decrease the surface tension of the oil and increase the rate of oxygen diffusion from the headspace air into the oil to accelerate oxidation (Mistry and Min, 1987). Therefore, it is essential that several practical loading and unloading configurations and management procedures are used.

TANK DESIGN

Design of storage tanks is not only important for minimizing the amount of oil surface exposure, which promotes oxidation, but is also important for facilitating complete removal of oil in between batches. **Figure 1** shows examples of poor horizontal tank designs (left) that lead to high surface are of air exposure. Use of vertical tanks (right) are preferred because of less surface area of air exposure of oil near the top of the tank and better drainage for complete oil removal.

Good tank design also includes having a sump area slightly lower than the port for the exiting oil **(Figure 2).** This serves two purposes. First, it allows sediment to remain below the withdrawal area of the tank, which is beneficial for lipid products that have high amounts of contaminants. Secondly, it can reduce cleaning time by utilizing a sump port to remove the unwanted material from the tank from the lowest point possible.

During storage, a container or tank should be filled as completely as possible to minimize the amount of headspace and oxygen exposure. Peroxide formation also is a linear function of surface-to-volume ratio (Su, 2003). Going (1968) evaluated the effect of container size on the oxidative deterioration of refined, bleached soybean oil stored at 48.9°C for 5 weeks and showed that oxidation is not only a function of time and temperature, but is also a function of surface area. As the container size increases, the surface-to-volume ratio decreases, and production of peroxides is a linear function of surface-to-volume ratio. These results indicate that lipid storage tanks need to be filled as completely as possible to minimize the surface-to-volume ratio.

Figure 1. *Comparisons of good and bad tank designs for minimizing air exposure (Source: Gupta, 2017).*

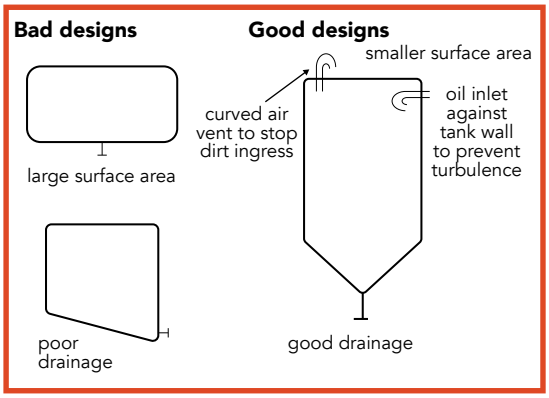
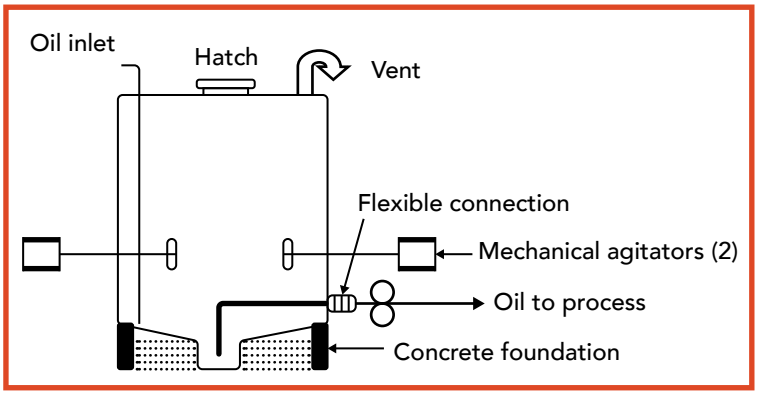


Figure 2. *Example of an ideal lipid storage tank design (Source: Gupta, 2017).*



MECHANICAL AGITATORS

While it is common for most fat and oil tanks to not contain agitators for mixing, they should be considered as important features in an ideal soybean oil storage tank because of the need to ensure adequate mixing of antioxidants that may be added to minimize oxidation. Simply adding antioxidants to the top surface of oil storage tanks after filling is not an effective use of an antioxidant because it is not homogeneously mixed with the entire oil mass in the tank. However, it is important to select low shear, low turbulence propellers to minimize splashing and air exposure during mixing **(Figure 3).** Alternatively, adding antioxidants using flow meters during loading is preferred to ensure a uniform mix without the need for subsequent agitation. Use of mechanical agitators is discouraged because any movement of the oil results in exposure to air in the headspace of the tank. However, this can be counteracted by applying nitrogen gas in the headspace of the tank.

If agitators are used, they should be placed at a height that will ensure submersion in the oil for much of the time as oil is removed, and should not be placed vertically to cause splashing of oil. Aeration of oil should be avoided at all times. Controlling agitators using a fill switch (flotation or ultrasonic measuring devices) is useful so that they can be stopped once the height of the oil in the tank is a certain height above the blades. An example of a side-mount horizontal motor for mixing is shown in **Figure 4.**

Figure 3. *Examples of low shear, low turbulence propellers for oil storage tanks. (Source: J. Lechman, J&R Consultants, Ltd., Winnipeg, MB, Canada).*

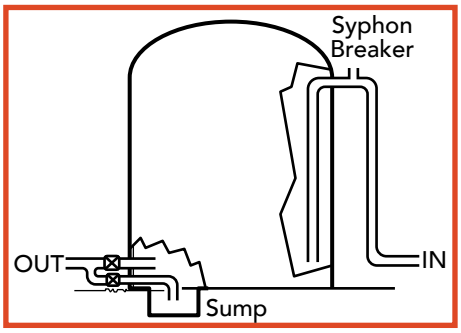
Figure 4. *Example of a side-mount horizontal motor for mixing (Source: J. Lechman, J&R Consultants, Ltd., Winnipeg, MB, Canada).*

SAFE-FILL AMOUNT

When filling tanks or IBC's for oil storage, it is important to consider the expansion behavior of the oil based on the temperature of the oil at the time of loading. When temperature is increased, the oil density decreases and increases the volume. Therefore, oil storage tanks should have a designated "safe-fill" level to account for the changes in density (coefficient of cubic expansion) to avoid over filling or overflowing due to expansion of storage tanks resulting from temperature changes of oil (Figure 5). Tanks and containers should also have vents that protect them from negative and positive pressures.

Figure 5. *Example of external measure of existing tank volume (Source: J. Lechman, J&R Consultants, Ltd., Winnipeg, MB, Canada).*

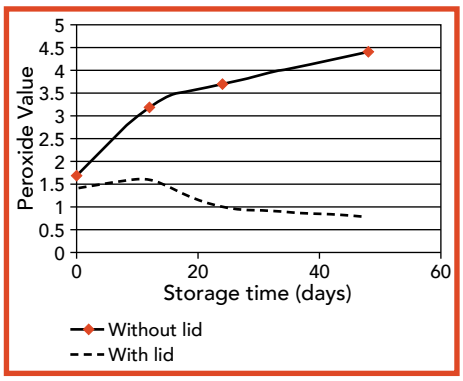
Figure 6. *Example of a bottom loading configuration for filling fat and oil storage tanks (Source: J.P. Burkhalter. 1976. J. Amer. Oil Chem. Soc.. 53:332-333.)*



TANK LOADING

When loading oil tanks, the use of bottom filling is preferred over top filling because it does not expose the soybean oil to air as it falls into an empty tank from a top loading pipe **(Figure 6).** Empty tanks contain atmospheric contaminants such as air (oxygen) and moisture (humidity). Gravity dropping high quality oils from the top of the tank leads to oxidation and hydrolysis before the tank is even filled. Oil is highly vulnerable to oxidation at the time of tank loading because the surface area of the entire volume of oil being loaded is exponentially increased, and using antioxidants in this situation will minimize their effectiveness.

Figure 7. *Effects of using covered storage from minimizing oil oxidation (Source: Berger, 1994).*



After tank loading is completed, avoid forcing air through pipes to remove the remaining oil. In addition, avoid steam blowing or flushing with anything else except for nitrogen. If nitrogen isn't available and flushing is required, flush these materials into a refuse collection container to avoid oxidizing the high quality oil in the tank. Although the elimination of air in the headspace of a tank prevents oxidation, complete elimination of air is impractical. The solubility of oxygen in soybean oil is quite high (2.1 mL/100 mL) at 22 to 23°C, and is sufficiently soluble to yield a peroxide value of 18 mEq/kg (Aho and Wahlroos, 1967).

TANK COVERS

While most fat and oil storage tanks are covered or have lids, some do not. **Figure** 7 shows the effects of oxidation (measured as changes in peroxide value) when using a lid or cover compared to not covering (Berger, 1994). Lids of tanks should always be used and properly attached. Simply slipping the lid over the inlet doesn't ensure that the inlet will be covered, especially in extreme weather conditions (wind and rain).

NITROGEN APPLICATIONS

Exposure to oxygen during soybean oil handling and storage is a primary cause of oxidation. Therefore, minimizing or eliminating oxygen exposure is critical for long-term preservation of soybean oil quality. When oil is stored under a vacuum or air exposure is replaced with nitrogen gas, oxidation does not occur (Shahidi, 2005). While using vacuum storage is impractical under most commercial conditions, the use of nitrogen gas to remove and replace air in the headspace of oil storage tanks and flushing out pipes after filling provides an additional level of protection from oxidation. This method is routinely used for edible grade soybean oil and other vegetable oils to minimize oxidation during extended periods of storage. Displacement of oxygen (< 2%) in the storage tank or con-

tainer headspace with nitrogen or carbon dioxide has been shown to be effective in reducing oxidation in vegetable oil (Bishov et al., 1971). Therefore, the use of nitrogen or other inert gases should be considered whenever the oil is to be stored for an extended period time or maintained at hot temperatures. Specialized equipment is commercially available for installation in oil storage tanks.

Nitrogen is generally applied using either nitrogen sparging or nitrogen blanketing. Nitrogen sparging incorporates nitrogen micro bubbles into the oil during tank loading **(Figure 8),** while nitrogen blanketing displaces air in the headspace of oil storage tanks **(Figure 9).** When utilizing nitrogen blanketing, the pressure inside of the oil storage tanks is maintained between 2 and 15 pounds per square inch (psi), which adjusts accordingly to the volume of oil in the tank. This is typically accomplished by using a fully automated process with safeguards that include using pressure regulated vents to allow for excessive gases to be exhausted to the atmosphere. Nitrogen gas for these applications is generally available from local suppliers, which provide a nitrogen storage tank. Alternatively, a nitrogen generator can be purchased and used onsite to supply nitrogen as needed. In either case, nitrogen gas should be highly concentrated (99.998%), with greater purity (99.999%) available from some suppliers at a higher cost. Because lipid oxidation is an irreversible process, utilizing nitrogen sparging, blanketing, or a combination of both is recommended to protect soybean oil from further oxidation upon delivery.

Figure 8. *Example of valve for introducing nitrogen gas through loading in a storage tank (Source: L. Inturrisi, Technical director, Mewah Oils, 10th AOCS Bienniel Meeting – Lipid Analysis and Oxidation Short Course, Barossa Valley, S. Australia, September 11, 2017).*

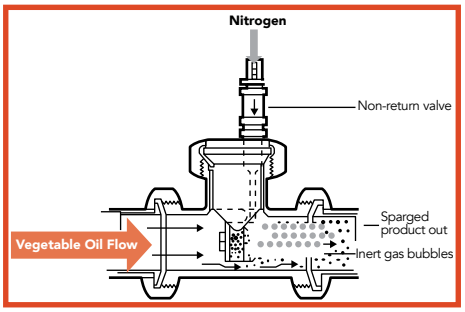
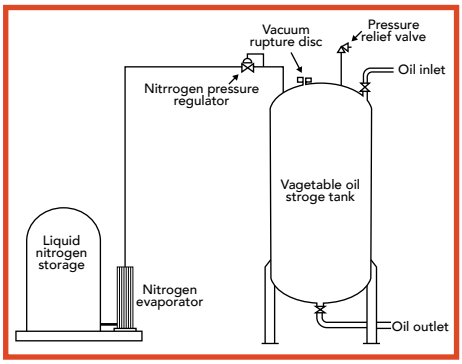


Figure 9. *Simple nitrogen blanketing system (Source: Bailey's Handbook - Storage, Handling, and Transport of Oils and Fats - Gary R. List, Tong Wang, and Vijai K.S. Shukla)*



TANK UNLOADING

Managing inventory of multiple oil tanks is also important for minimizing air exposure in the headspace of individual tanks. Storage capacity of oil at a feed mill should be based on rapid inventory turnover (less than one week). A "first-in-first out" inventory management approach is also essential for minimize storage time of oil individual tanks. Once oil begins to be removed from one tank, the process should be continued until the tank is empty before beginning to use oil from a subsequent storage tank. This is important to minimize head space air exposure during oil discharge, especially if nitrogen gas is not being used to displace air. Another important consideration is to have available a "carry-over" tank that allows unloading any remaining oil in any of the main oil storage tanks so that the new oil delivery will not be compromised by the existing oil in the tank. This management procedure is especially important if storage tank cleaning is not performed regularly or if using flat bottom tanks where sediment accumulates.

Table 2. *Effects of metals on oxidative stability of soybean oil (peroxide value after 20 hours of active oxygen method test)*

Metal ion	Concentration, ppm	Peroxide value (mEq/kg)
Control	0.0	47
Fe^{+++}	3.0	293
Mn^{++}	3.0	85
Cu^{++}	0.3	288

Source: Kemin Industries, Inc.

AVOID USING COPPER AND BRASS PIPES AND FITTINGS

Copper and iron are powerful prooxidant metals that are naturally present in small quantities (2.5 ppb and 0.20 ppm, respectively) of refined soybean oil (De Leonardis and Macciola, 2002). Studies have shown that these transition metals promote oxidation **(Table 2).** Therefore, use of copper or brass fittings, pipes, or tubing must be avoided when handling fats and oils because they promote oxidation. Safe materials for handling soybean oil include neoprene, aluminum, carbon steel, plastic, and stainless steel.

However, the use of metal chelators such as phosphoric acid, citric acid, ascorbic acid, and EDTA (ethylenediaminetetraacetic acid) have been shown to decease oil oxidation by converting copper and iron ions into insoluble complexes between metals and lipid peroxides (Halliwell et al., 1995). In fact, Min and Wen (1983) reported that the addition of increasing concentrations of citric acid to soybean oil linearly reduced oxidation during storage, and the addition of 150 ppm of citric acid was necessary to overcome the oxidative effects of 1 ppm of iron.

MINIMIZING FURTHER THERMAL EXPOSURE

Although it is difficult under most practical situations to minimize exposure to ambient temperatures, which promote oxidation, some simple management factors can still be implemented. When possible, locate oil storage tanks inside covered warehouses or storage facilities to prevent direct sunlight and heat exposure. Also paint the exterior of oil storage tanks with white or other light colors to promote reflection rather than absorption of heat, such as when black or dark colored paints are used. There are several commercially available heat reflective coatings which can minimize heat penetration into the oil in a storage tank by providing much cooler tank surfaces.

COMMERCIAL ANTIOXIDANTS

One of the many positive attributes of soybean oil is that it contains relatively high concentrations of tocopherols and tocotrienols, which serve as natural antioxidants, compared with other fats and oils. As a result, these natural antioxidants are initially used to prevent oxidation of soybean oil until they are depleted. **Table 3** shows that the antioxidant activity of soybean oil containing 1,500 ppm of naturally occurring tocopherols provides significant amount of antioxidant protection compared to when carbon black

was used to remove tocopherols from the oil (45 ppm; Frankel et al., 1959). However, depletion of natural tocopherol content in soybean oil can occur rapidly, making it necessary to use commercial synthetic antioxidants to prevent further oxidation of soybean oil.

Many synthetic antioxidants are commercially available that have been shown to be effective for preventing further oxidation of soybean oil. Common active ingredients in these commercial antioxidants include ethoxyquin, tertiary-butylhydroquinone (TBHQ), butylated hydroxy anisole (BHA), butylated hydroxytoluene (BHT), propyl gallate, ascorbic acid or palmitate, and citric acid. However, it is important to select the appropriate antioxidant for addition to soybean oil because these products vary in their effectiveness among various types of fats and oils. As shown in **Table 3,** the greatest protection (hours before reaching a constant peroxide value) from oxidation of soybean oil was when 0.57 mmol/kg oil was added from ascorbic acid and 0.01% citric acid, alone or in combination with BHA, BHT, or α-tocopherol. Another comparison of the effectiveness of commercial antioxidants in soybean oil based on extent of thermal exposure is shown in **Table 4.** Note that TBHQ and ascorbyl palmitate were most effective in preventing soybean oil oxidation at 45°C, while ascorbyl acid and TBHQ were most effective at 98°C. Azeredo et al. (2004) evaluated the extent of oxidation in refined soybean oil during a 6 month storage period at 25°C under a constant illumination (1720 lux) by combining different primary antioxidants (TBHQ, β-carotene, citric acid) to the oil or using and ultraviolet light absorber (Tinuvin P) in PVC bottles. Results showed that TBHQ was the most effective, followed by Tinuvin P in reducing oxidation of soybean oil, and the use of Tinuvin P prevented changes in oil color. Consult your antioxidant supplier for the most appropriate antioxidant products to use for your climatic conditions, and the recommended dosage rates.

It is also important to ensure that when antioxidants are added to soybean oil in storage tanks, that they are uniformly applied and homogenously mixed to maximize their effectiveness. Adding antioxidants to the top of the oil in a tank is not recommended, unless there are low shear agitators for mixing, because antioxidants do not homogeneously disperse within the oil mass due to difference in bulk density and other chemical properties between the two liquids. Therefore, the use of flow meters and dosing controllers on incoming and outgoing pipes are recommended for uniform application and mixing of antioxidants with soybean oil for maximum effectiveness.

Table 3. *Effect of various antioxidants and metal inactivators on soybean oil oxidation (adapted from Frankel et al., 1959)*

Antioxidant(s)	Antioxidant Activity[1]
Control (1,500 ppm tocopherol)	26
C-treated[2] (45 ppm tocopherol)	17
C-treated + ascorbic acid[3]	43
C-treated + BHA[3,4]	18
C-treated + BHA +0.01% citric acid[3]	56
C-treated + BHT[3,5]	23
C-treated + BHT + 0.01% citric acid[3]	53
C-treated + citric acid[3]	50
C-treated + propyl gallate	26
C-treated + α-tocopherol	21
C-treated + α-tocopherol + 0.01% citric acid	53

[1]Hours based on peroxide value of soybean oil.
[2]Carbon black treated oil to partially remove natural tocopherols.
[3]Antioxidant concentration was 0.57 mmol/kg oil.
[4]BHA = butylated hydroxy anisole.
[5]BHT = butylated hydroxytoluene.

Table 4. *Effect of various antioxidants on oxidation of soybean oil (adapted from Cort, 1982)*

Antioxidant (0.02%)	Antioxidant Activity[1]	
	45°C[2]	98°C[3]
Control (no antioxidant added)	168	5
Ascorbyl acid	288	43
Ascorbyl palmitate	456	13
Butylated hydroxyanisole (BHA)	216	9
Butylated hydroxytoluene (BHT)	240	11
Propyl gallate	360	14
Tertiary-butylhydroquinone (TBHQ)	544	28

[1]Hours to reach peroxide value of 70.
[2]Oxidation at 45°C as a thin layer of oil.
[3]Oxidation at 98°C at AOM conditions.

SEDIMENT REMOVAL

Regardless of the fat or oil source used, there will be varying amounts of insoluble impurities that cause sediment and promote oxidation. Therefore, filtration systems should be installed and cleaned weekly when filling tanks with oil as well as discharging oil tanks for adding oil to finished feeds in a feed mill. This is a relatively low cost and effective method of preventing further oil oxidation and reducing cleaning time of storage tanks, pipes, and fittings. Filters (strainers) should be located in two positions of the oil tank storage and handling system. One filter should be located at the first point of contact between the incoming oil and the tank system. This is to provide the first line of filtration against contaminants that could be coming from outside the system. A second filter should be located at the earliest point of the tank discharge system before entering the feed mill, of filling tanker trucks, IBC's and carry-over tanks. Because oil oxidation and hydrolysis lead to the creation of sediment, filtering all outgoing oil provides additional value for maintaining cleanliness in the feed mill or distribution system. Figure 10 shows examples of a typical stainless-steel basket filter.

Figure 10. *Enclosed stainless steel basket strainer (left), exposed basket strainer showing the strainer inside the cavity (center), external view of extracted strainer (right). Source: J. Lechman, J&R Consultants, Ltd., Winnipeg, MB, Canada.*

Figure 11. *Example of sediment collected from an oil storage tank. (Source: J. Lechman, J&R Consultants, Ltd., Winnipeg, MB, Canada).*

TANK CLEANING

Depending on the inventory turnover of lipids in individual storage tanks, the tanks should be cleaned at least every 3 months to remove sediment on walls and bottoms before a new batch of oil is added. **Figure 11** shows an example of sediment collected from an oil storage tank after several months. There are specialized, commercially available cleaning products for specific types of fats or oils being used. Various types of vegetable oils are classified based on their drying, non-drying, or semi-drying properties, which affects the type of cleaning product that will be most effective for complete cleaning. Oils such as coconut oil, palm oil, palm kernel oil, and olive oil have iodine values less than 110 and are classified as non-drying oils. Semi-drying oils have iodine values between 110 and 140, while drying oils, such as soybean oil have iodine value between 140 and 190, and create solid residues on the surfaces of oil storage tanks that is difficult to remove.

Several commercially available cleaning products that are appropriate for soybean oil can be applied using a hand sprayer or power washers with a foaming nozzle to all surfaces of oil storage tanks. Recommendations for the most effective cleaning products for soybean oil storage tanks and conditions for their use can be obtained from reputable manufacturers and suppliers of these products. For some cleaning products, some manufacturers recommend beginning using water at a cooler temperature and gradually increase water temperature with repeated pressurized spraying on the internal tank surface. However, it is important to note that both caustic and acidic cleaners are used in tandem (separately) to break down different compounds along the walls of the equipment. These same cleaning products should also be used to clean pipes, fittings, and strainers which are involved in the distribution system of the oil.

SUMMARY

The production of U.S. crude, degummed soybean oil results in a high quality oil that is minimally oxidized for use in swine and poultry diets. However, because soybean oil contains high amounts of polyunsaturated fatty acids, it is highly susceptible to oxidation during transport from the soy crushing plant, at storage facilities at feed mills, and when incorporated into complete feeds that are transported and fed on commercial farms. To preserve the high quality and energy value of U.S. soybean oil, numerous oil storage design and distribution factors must be managed to minimize air, light, and transition metal exposure to reduce oxidation throughout this process and capture the greatest nutritional and economic value. The first factor to consider is knowing your soybean oil source and how it is managed from production until delivery. Once soybean oil has been delivered, numerous management steps should be implemented to prevent oxidation of oil from occurring until it is incorporated in complete feeds. Design factors include optimal tank configuration for bottom loading, considerations for using mechanical agitators, tank covers, and avoid using copper and brass fittings and pipes. Proper management should include the use of nitrogen to displace air in tank headspace, minimizing excessive heat exposure, use of commercial antioxidants, sediment removal with in-line filters, "first-in-first out" inventory management, using "carry-over" tanks to remove remaining oil before filling with fresh oil, and tank cleaning. If all of these design and management factors are achieved, the full benefits of using high quality U.S. soybean oil in swine and poultry feeding programs can be achieved. The appendix "U.S. Crude Soybean Oil Quality Assurance Guide and Checklist" provided with this chapter can be used as a useful guide for determining opportunities to improve soybean oil quality management in feed mills.

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APPENDIX

Lipid Procurement Checklist - USSEC	Date:					
Procurement Assessment						
Product type and name:	Vegetable Oil	Animal Fat	Blend	Other		
Were product specifications and a certificate of analysis provided?	Yes		No			
Are the product specifications approved by the nutrition department?	Yes		No			
Risk assessment:	High	Medium	Low			
Expected transit time from origin to destination:						
Was an antioxidant applied before departing from supplier?	Yes		No			
If yes, what was the product name, type, and dosage rate?						
Shipping Assessment						
Risk factors:	Temperature	Time	Contamination	Air	Moisture	
Conveyance:	Sea Vessel	Land Tanker	Container	IBC/Tote		
Did your order fill the transport vessel?	Yes		No			
If no, what is the difference from full capacity?	<50%		<75%			
Headspace management:	Fill	Nitrogen Blanketing	None			
Were enroute temperature measuring systems used?	Yes	No	N/A			
Were there any temperature spikes during transport?	Yes	No	N/A			
Is a temperature data logger available?	Yes	No	N/A			
Is the disharge line of the vessel flushed before emptying?	Yes	No	N/A			
Is that same line purged with nitrogen before unloading?	Yes	No	N/A			
What is the cleaning protocol for the transport vehicles tank?						
Is the discharge port of the tank at the lowest point possible (trailer)?	Yes	No	N/A			
Receiving Assessment						
Which receiving tank(s) were cleaned prior to delivery?	Tank 1	Tank 2	Tank 3	Tank 4	Tank 5	Mani-fold
Was a de-greaser or de-scaler used to clean them?	Yes		No			
What is the name of the product used to clean the tanks?						
After the tank is cleaned, how is it dried and prepared for filling?	Hot Air	Blown Atmospheric Air	Nitrogen Blanket	Nothing		
Are there filters in place for incoming and outgoing product?	Yes-Incoming	No-Incoming	Yes-Outgoing	No-Outgoing		
How often are the filters cleaned?						
How is the tank filled?	Top		Bottom			
What is the volume or pressure of the pump used to fill the tanks?						

Receiving Assessment				
How much time did it take to receive your order? What volume did you receive?				
Do the receiving lines need to be flushed after unloading?	Yes		No	
If yes, explain how that is done.				
Is product from the previous order (carryover) remining in the tank or blended?	Yes		No	
Is carryover product moved to another tank before refilling?	Yes		No	
If yes, what is the tank identifier?				
Does the new received product match the appearance of previous samples?	Yes		No	
Does the new received product match smell of previous samples?	Yes		No	
Are your staff aware of the proper protocols for sampling and handling oil samples?	Yes		No	
Was a sample retained at the beginning of receiving?	Yes		No	
Was a sample retained at the end of receiving?	Yes		No	
What was the temperature of the product at delivery?				
Are the connections and related plumbing comprised of approved materials?	Yes	No	Identifed Copper / Iron / Brass Fittings	

Incoming Tank/Product Sampling				
Tank Identifier	Incoming Tracking #	Where was the sample taken?	Carryover Tracking #	Where was the sample taken?
Tank 1				
Tank 2				
Tank 3				
Tank 4				
Tank 5				

Storing Assessment				
Where are the tanks that store the oil?	Inside	Outside	Underground	
If the tanks are outside, are they out of direct sunglight?	Yes	No	N/A	
How are the tanks positioned?	Horizontally	Vertically		
Do the tank(s) resemble a silo shape or are they as wide as tall?	Taller than Wide	Wide as Tall		
What are the tank dimensions and volumes?				
What is the exterior color of the tanks?	White	Black	Other	
Is there signficant headspace of the tank when less than full?	Yes	No		
Are the tanks insultated from the outside air temperature?	Yes	No		
Is the discharge cleaning port at the lowest point (sump) of the tank?	Yes	No		
Is the port for outgoing product higher than the drain port or are they of equal height?	Yes	No	Equal	
Where are the sampling ports in the tanks?	Bottom	Bottom 1/3	Middle	Top 1/3
Are the tanks made of an appoved material?	Yes	No		
Do the tanks have accurate internal thermostats?	Yes	No		
Is there a device to measure the fill level of the tank?	Yes	No		
What is the average headspace of the tank after filling?	>50%	<50%	<75%	None-Full
Is nitrogen sparging or blanketing used?	Blanketing	Sparging	None	
Are there agitators in the tanks?	Yes	No		
If yes, what is the height of the agitators?				
How are the agitators controlled?	Manually	Automated	No Agitators	
Are the agitator propellers designed to reduce splashing and turbulence?	Yes	No		
Are supplemental antioxidants added?	Yes	No		

Storing Assessment		
If yes, how is the antioxidant added to the system?		
What is the product name of the antioxidant?		
If an antioxidant is added, what is the addition rate per tonne?		
Has the procedure for adding an antioxidant been verified?	Yes	No
What is the length of the tank discharge lines?		
Are the tank discharge lines temperature protected?	Yes	No
Are there check valves in operation?	Yes	No
Are the lids of the tanks propely sealed?	Yes	No
Is there any spot where air and moisture could be introduced to the system?		
Supplementary Decisions		
Does your procurement manager have a copy of this?	Yes	No
Does your nutritionist have a copy of this?	Yes	No
Special Notes:		

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Type of products being used: *e.g. vegetable oil, animal fat, blend, acid oil*	1)
	2)

Tag - Product 1	Yes	No	Name of product from supplier - Product 1)	Yes	No
Tag - Product 2	Yes	No	Name of product from supplier - Product 2)	Yes	No

Expected transit time from origin to destination, Product 1)	Type of Conveyance, Product 1)
Expected transit time from origin to destination, Product 2)	Type of Conveyance, Product 2)

Antioxidant applied prior to shipping, Product 1	Application rate, Product 1)
Antioxidant applied prior to shipping, Product 2	Application rate, Product 2)

Date Taken	Name	Tracking #	Sample Name	Company	Temperature	Status	Anti-Oxidant	Peroxide Value (meq)	Free Fatty Acids	Anisidine Value	Notes
4-05-2019	John Doe	98764	Yellow Grease	XYZ	30	Empty	No	5	15		
4-20-2019	John Doe	98764	Yellow Grease	XYZ	30	Received	No	5	15		
5-25-2019	John Doe	98764	Yellow Grease	XYZ	33	Stored	No	15	35		
6-27-2019	John Doe	98765	Yellow Grease	XYZ	30	Empty	No	4	15		
6-28-2019	John Doe	98765	Yellow Grease	XYZ	30	Received	No	7	20		
7-25-2019	John Doe	98765	Yellow Grease	XYZ	33	Stored	No	20	40		
2-01-2019	John Doe	123455	Soybean Oil	ABC	30	Received	Yes	1	1		
2-15-2019	John Doe	123455	Soybean Oil	ABC	30	Stored	Yes	1	2		
3-15-2019	John Doe	123455	Soybean Oil	ABC	30	Empty	Yes	3	5		
4-22-2019	John Doe	123456	Soybean Oil	ABC	30	Received	Yes	1	1		
5-05-2019	John Doe	123456	Soybean Oil	ABC	30	Stored	Yes	2	5		
6-20-2019	John Doe	123456	Soybean Oil	ABC	30	Empty	Yes	11	7		

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Capacity, Inventory, and Anti-Oxidant Management

3 Step process to understanding the following…

1) Site Capacity
2) Inventory
3) Anti-Oxidant Requirements

1) Site Capacity

Tank Identifier	Height	Diameter	Volume m^3 not including the cone	Low Temp Capacity (tonnes) 20.0° C	High Temp Capacity (tonnes) 35.0° C	
T1 - CD-SBO	14.00	7.00	538.78	494.71	490.03	*1*
T2 - CD-SBO	12.00	6.00	339.29	311.54	308.59	*1*
T3 - CD-SBO	12.00	6.00	339.29	311.54	308.59	*1*
T4 - YG	12.00	6.00	339.29	311.54	308.59	*1*
T5 - YG	12.00	6.00	339.29	311.54	308.59	*1*
Totals			*1,895.95 m^3*	*1,740.86 tonnes*	*1,724.41 tonnes*	

2) Inventory

Tank Identifier	Capacity (tonnes)	Carryover Tonnes	Percent Capacity	Available Tonnage for Filling	Directed Tonnes into Tank(s)	Percent Capacity
T1 - CD-SBO	490.03	0.00	0.00 %	490.03	485.00	98.97 %
T2 - CD-SBO	308.59	20.00	6.48 %	288.59	285.00	98.76 %
T3 - CD-SBO	308.59	0.00	0.00 %	308.59	305.00	98.84 %
T4 - YG	308.59	3.00	0.97 %	305.59	300.00	98.17 %
T5 - YG	308.59	5.00	1.62 %	303.59	300.00	98.82 %

3) Anti-Oxidant Requirements

Anti-Oxidant Inclusion Rate (kg/mt) 2.00

Tank Identifier	Total Tonnes in Tank	Required Anti-Oxidant per Tank
T1 - CD-SBO	485.00	970.00
T2 - CD-SBO	285.00	570.00
T3 - CD-SBO	305.00	610.00
T4 - YG	300.00	600.00
T5 - YG	300.00	600.00

total requirement of anti-oxidant in kilograms: 3,350.00

Application Recommendations			
	<10°C	10°C - 25°C	>25°C
Finished Feed	100-200 g/MT	150-300 g/MT	250-500 g/MT
Premixes	750-1250 g/MT	1250-1750 g/MT	1750-2250 g/MT
Fats	1000-1750 g/MT	1750-2500 g/MT	2500-3500 g/MT
Meals	1750-2500 g/MT	2500-3250 g/MT	3250-4000 g/MT

***The C indicates environmental temperature**
****Above dosage rates are for typical matrix and humidity conditions. Contact you Novus Technical Service Representative to receive a custom dosage rate optimized for your needs and matrices.**

Rules for more Consistent Results from your Samples

Take your sample from clean a discharge port.

Prevent outside contaminants from the discharge port from causing misrepresented analytical values. Take the time to clean the area from which you are obtaining the sample. Do not touch the inside of the sample container or sample itself to prevent possible contamination. Pre-label your containers with something that will maintain its visibility under varying conditions.

Keep lipid samples in a glass or non-transparent (opaque) container.

Oxidation factors such as oxygen, light, and heat can alter sample chemistry. Remember that a sample should be representative of the entire batch of oil, and the sample will adjust to its atmostpheric conditions more aggressively which could result in inaccurate analytical results. Glass containers are preferred because they do not expand when frozen. Some plastic containers have UV films as part of their composition to block light. Light can also be blocked in glass containers by placing them in brown paper bags.

Store lipid samples in a refrigerator or freezer.

Because oil samples are in a constant state of oxidation, storing them in an environment that minimizes further oxidation until analysis is critical. The analytical results obtained are a direct reflection of how the product was stored before analysis. Freezing is the preferred for storing lipid samples until analysis, but refrigeration is always better than storing at room temperature.

Ensure samples are collected, stored, and submitted in a timely manner.

Analytical laboratories typically have no information about hwo lipid samples were collected and stored prior to receving them for analysis. When submitting samples to a commercial laboratory for analysis, always indicate how you want the sample(s) to be stored prior to analysis. If this option isn't available, only submit samples early in the week so that your sample integrity isn't compromised by storing it over a weekend before analysis can be performaed. This same approach should be used for transporting samples. Do not let samples sit overnight or over the weekend in trucks or in the office. Exposure to any environmental conditions beyind freezing will only lead to a reported value that is different from the oxidation conditions at the time of sample collection.

Ensure in-house equipment is Calibrated.

The best samples can be misrepresented by inappropriate analysis procedures. Always ensure that approved AOCS procedures are used and specified in the analysis report, and request documentation that the analytical equipment used was properly calibrated. Avoid using NIR (Near Infared Sprectroscopy) results for determining lipid composition unless there is ample information provided by the analytical laboratory to verify accuracy of calibrations and results. If photometric testing equipment is used, analyze a known control sample to verify accurate readings.

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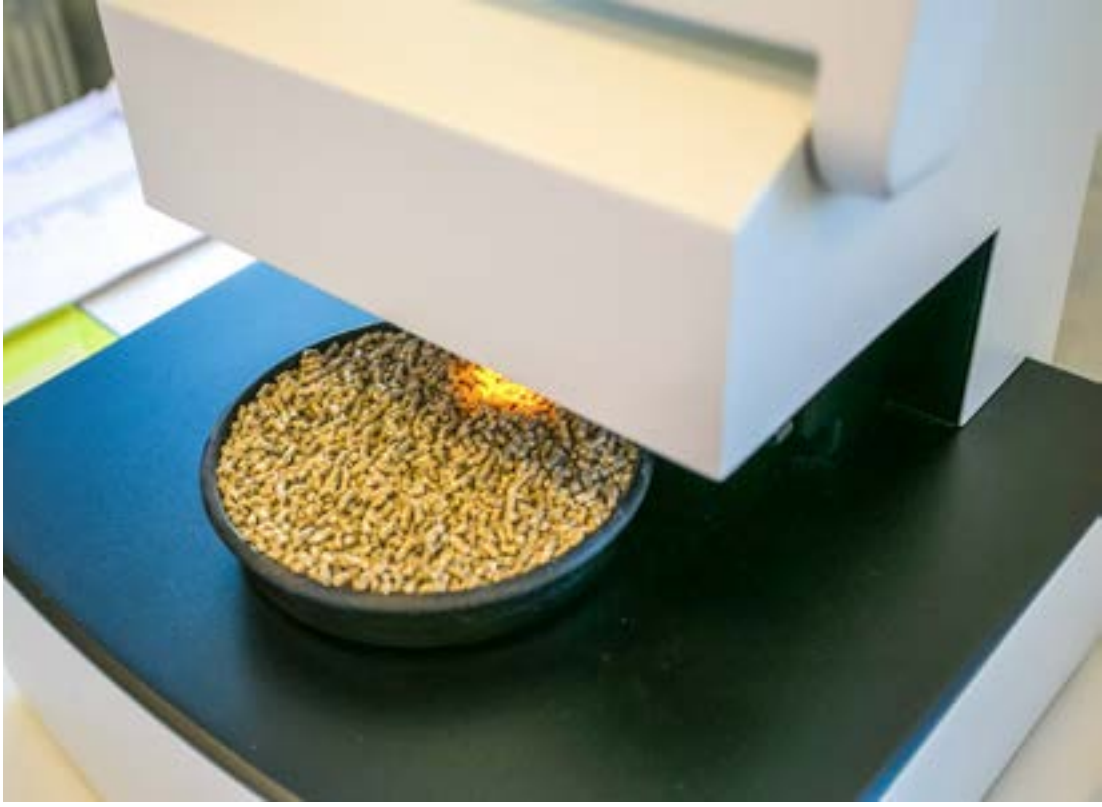

Chapter

07

Role of U.S. Soybean Oil in Manufacturing High Quality Feeds

INTRODUCTION

Manufacturing high quality swine and poultry diets is essential for achieving optimal nutrition, and the addition of soybean oil as a supplemental energy source to animal feeds plays an important role in these processes. Swine feeds are commonly produced in mash (meal) form or they are pelleted, especially for weaned pig diets or if complete feeds are transported for long distances from the feed mill to the farm. In contrast, most broiler and layer diets are pelleted.

For mash diets, soybean oil has been shown to be effective in reducing dust levels in feed mills and confinement swine facilities. Dust control is essential for minimizing adverse effects on respiratory health of humans working in these facilities, as well as for animals in confinement production facilities. In addition, minimizing dust in feed mills and animal facilities prolongs the longevity and functionality of equipment over time, and reduces maintenance and replacement costs.

Pelleting is the most common thermal processing method used for manufacturing swine (Miller, 2012) and poultry feeds (Abdollahi et al., 2013). Compared with feeding mash diets, pelleted diets provide several advantages including increased bulk density to reduce storage space, improved handling characteristics, along with reduced dustiness, ingredient segregation during transport, pathogens, and sorting of large particles which can occur when feeding mash diets (Abdollahi et al., 2012; NRC, 2012). In addition, pelleting diets also improves feed conversion resulting from reduced feed wastage and increases digestibility of energy and nutrients (Richert and DeRouchey, 2010; NRC, 2012). However, the addition of soybean oil to pelleted diets can reduce the pellet durability index (PDI) if not properly managed. A significant reduction in PDI is usually associated with an increase in fines and can lead to suboptimal growth performance in swine and poultry. Therefore, it is important to understand the effects of soybean oil on pellet quality, and approaches that can be used to optimize pellet quality when soybean oil is included in the feed formulation.

THE ADDITION OF SOYBEAN OIL TO MASH DIETS SIGNIFICANTLY REDUCES DUST IN FEED MILLS AND CONFINEMENT SWINE FACILITIES

Feed mills generate a tremendous amount of dust through various processes including particle size reduction (grinding) of grain, mixing of ingredients, movement through augers and conveyors, and loading into storage bins and trucks. The addition of fats and oils to feed ingredients and complete feeds during the early stages of the feed manufacturing process is a practical and effective method for minimizing dust in feed mills. For example, Mankell et al. (1995) compared the effects of dietary soybean oil supplementation level (0, 1, or 3%), corn bulk density (normal = 730 kg/m3; low = 600 kg/m3), time of oil addition (before or after grinding the corn), and storage time (0, 7, and 14 days) on dust produced from feed. Results of this study showed that adding 1% soybean oil markedly reduced dust concentrations, and the addition of 3% soybean oil resulted in further reduction in dust **(Table 1).** A greater amount of dust was generated from grinding low bulk density corn than normal corn. Therefore, soybean oil additions greater than 3% may be needed when using low bulk density corn to achieve the same amount of dust reduction as observed for normal corn. Dust reduction was also more effective when soybean oil was added to complete feed after grinding than when it was added to corn before grinding. However, feed storage time had no effect on dust suppression when soybean oil was added. These results clearly show the significance of using soybean oil to substantially reduce dust in feed mills.

Table 1. *Logarithm transformed dust data from 12 kg of feed with varying percentages of soybean oil, corn bulk density, time of oil application relative to grinding, and storage time (adapted from Mankell et al., 1995)*

Soybean oil, %	Corn bulk density, kg/m³	Time of oil application relative to grinding	Storage time, days			
			0	7	14	Overall
0	730	-	3.381	3.312	3.301	3.331[b]
0	600	-	3.604	3.819	4.090	3.838[c]
1	730	Before	1.914	1.923	5.297	3.044[bd]
1	730	After	1.364	1.045	1.016	1.142[e]
1	600	After	1.898	2.221	2.219	2.113[d]
3	730	Before	-0.029	0.092	0.110	0.057[f]
3	730	After	-0.180	-0.313	-0.289	-0.261[g]
3	600	After	0.369	0.181	0.535	0.362[h]

[a,b,c,d,e,f,g,h]**Means with uncommon superscripts are different (P < 0.001).**

In addition to the need to control dust in feed mills, confinement swine facilities often have significant concentrations of dust and gases that can be detrimental to respiratory health of humans and pigs. Several studies have shown that when pigs are exposed to high concentrations of dust and gases, growth and feed efficiency is often reduced (Curtis et al., 1974) and respiratory health is compromised (Doig and Willoughby, 1971; Bundy and Hazen, 1975; Drummond et al., 1981). Dust particles that are smaller than 5.2 μm in diameter are capable of penetrating the lungs of humans and pigs (Anderson, 1958), and can be carriers of viruses and bacteria (Roller, 1961; 1965; Carlson and Whenham, 1967), which causes dust to be a health concern. Furthermore, dusty environments have been shown to reduce the longevity and operating efficiency of mechanical ventilation systems in confinement animal facilities (Person et al., 1977; Martin and Crisp, 1984). Therefore, efforts to control dust in confinement swine facilities is essential to minimize the adverse health effects on pigs and people.

Gore et al. (1986) evaluated the effects of adding 5% soybean oil to isocaloric corn-soybean meal nursery pig diets on growth performance and air quality (gases, dust, and bacterial colony counts). Results from this study showed that the addition of soybean oil to the diets had no effect of ammonia and carbon dioxide concentrations (which were very low, 1.1 to 2.8 ppm and 900 to 1,900 ppm, respectively) and growth performance, but dust concentrations were reduced by 45 to 47%, and total aerosol bacterial colony counts were reduced by 27% compared with feeding diets containing no supplemental soybean oil. These results were similar to those reported by Chiba et al. (1985) when 5% tallow was added to swine growing-finishing diets. Furthermore, Chiba et al. (1985) also reported a reduction in lung lesions of pigs fed the tallow diets compared with those fed diets without supplemental tallow. Wathes et al. (2004) evaluated growth performance responses of weaned pigs after 42 days of chronic exposure to airborne dust and ammonia in weaned pigs, and observed that growth rate and feed intake were reduced when pigs were exposed to dust concentrations of 5.1 mg/m3 and 9.9 mg/m3 (inhalable fraction) across ammonia concentrations of up to 37 ppm, but feed efficiency was not affected. These results indicate that the addition of lipids, especially soybean oil to swine diets fed in mash form, is effective in substantially reducing dust and aerosol bacterial counts, which can help maintain respiratory health and growth performance of pigs.

EFFECTS OF SOYBEAN OIL IN PELLETED DIETS FOR SWINE AND POULTRY

The 3 main goals of manufacturing high quality pelleted swine and poultry diets are to achieve high pellet durability and pellet mill throughput, while minimizing energy cost of the pelleting process. In general, achieving high pellet durability increases the likelihood that pellets will remain intact from the time of manufacturing until they are consumed by animals. However, almost any adjustment made to increase pellet durability decreases pellet mill throughput and increases energy cost (Behnke, 2006). Producing a high quality pellet is influenced by factors such as type of feed, quantity of fats and oils added, steam additives, particle size, moisture content, die characteristics, roller quality, and the gap between the roller and the die (California Pellet Mill Co., 2016). The primary contributors to energy use and cost during the pelleting process are the production of steam for the conditioning stage, and electricity (measured in kilowatt hours per tonne) required to operate the feeders, conditioners, pellet mill, and pellet cooling system. Most (up to 72%) of the energy used for pelleting is for steam conditioning (Skoch et al., 1983). Payne (2004) suggested that 15 to 10 kilowatt hours per metric tonne should be a reasonable goal for pelleting swine and broiler diets, respectively. Because of the many factors and complexity of the pelleting process, effective decision support systems have been developed to optimize pellet quality, production rate, and cost while only slightly decreasing pellet durability (Thomas et al., 1997).

Ingredient and nutrient composition of swine and poultry diets have a major influence on pellet quality, production rate and energy use. Cavalcanti and Behnke (2005a) evaluated the effects of starch, protein, lipid, and fiber content of diets on pellet quality using response surface designs, and showed a quadratic effect of starch content on PDI, with the maximum PDI values observed when diets contained 65% starch. There was an interaction between protein and starch content, where increasing the protein content reduced PDI, but PDI improved in the high starch diets. However, inclusion of lipid in the diet resulted in reduced PDI values, which appeared to be independent of any other dietary component. In a subsequent study, Cavalcanti and Behnke (2005b) evaluated pellet durability using 13 diets containing varying concentrations of corn, soybean meal, and soybean oil. The results were similar to their previous study, which showed that the highest PDI values were obtained when soybean oil inclusion rate was at the lowest levels. However, in this study, increasing dietary protein content resulted in improved pellet durability, but appeared to be better associated with the amount of soybean meal in the diet than with overall protein content. The effect of starch content on pellet durability was highly dependent on the proportion of other ingredients. These results, along with those reported by Stark (1994) and Briggs et al. (1999), suggest that the addition of lipid (e.g. soybean oil) to diets is generally expected to reduce pellet durability.

However, it is important to recognize that steam conditioning temperature is an important factor that not only affects pellet durability, but also has a significant impact on energy consumption. The use of the highest possible conditioning temperature has been shown to improve pellet durability and pellet mill energy consumption of diets containing no supplemental lipid or low lipid content, as well as improving pellet durability in diets containing high lipid content (Pfost, 1964). These effects may have been a result of increased steam conditioning causing a decrease in mechanical friction during pelleting (less temperature increase across the pellet die), resulting in decreased electrical energy consumption and improved pellet durability (Skoch et al., 1981). In addition, Pfost (1964) observed an interaction between dietary lipid content and pellet die length to diameter ratio (L:D), where pellet durability was affected by die L:D in low lipid diets, but was not affected by die L:D in high lipid diets. Fahrenholz (2012) suggested that dietary lipid content had a greater proportional effect on PDI than all of the other factors except conditioning temperature.

Other studies have shown that the addition of fats or oils before and after pelleting can both improve and decrease pellet quality, depending on the diet inclusion rate. One approach to achieve acceptable pellet quality is to add a low diets inclusion rate (1%) of lipid in the mixer before pelleting, and adding the remaining lipid after pelleting (Wamsley and Moritz, 2013). However, it is generally considered to be advantageous to add increased amounts of lipid during mixing and before pelleting to minimize reductions in nutrient digestibility and vitamin potency losses that may occur during the pelleting process, because fats or oils may decrease friction and heat generated between the pellet die and mash feed (Gehring et al., 2011). Briggs et al. (1999) reported that adding less than 5.6% lipid to diets containing about 20% crude protein did not reduce pellet quality, but Wamsley and Moritz (2013) observed that adding 3% lipid during mixing and before pelleting, when using a thicker die (44.9 mm), reduced pellet quality. Briggs et al. (1999) also showed that adding too much lipid (greater than 7.5%) at the mixer is detrimental to pellet quality. In contrast, Stark (1994) reported that the addition of relatively low concentrations (1.5% and 3%) of lipid decreased PDI by 2% and 5%, respectively. This reduction in PDI appears to be a result of reduced steam penetration and heat transfer due to lipid coating of feed particles, which adds moisture during the conditioning process. The decision of whether lipids are added pre- or post-pelleting should also be based on considerations of the risk of introducing pathogens to feed if fats or oils are added post-pelleting because of minimal exposure to inactivation temperatures used during the pelleting process (Lambertini et al. 2016).

Despite the potential reductions in PDI from adding supplemental fats and oils to diets, lipids serve as lubricating agents to reduce friction and heat generated through the pellet die by keeping moisture on the surface of the particles (Fahrenholz, 2012). This is especially important when pelleting pig starter diets containing high inclusion rates of milk products because they are susceptible to burning, which reduces amino acid digestibility. This lubricating effect of lipids may also have a positive effect on reducing energy consumption, but this effect does not always occur because of interactions with other processing variables or due to physical properties of the lipid source used (Briggs et al., 1999). Fahrenholz (2012) and Stark (1994) reported that dietary lipid content was one of the most influential factors affecting energy consumption of pellet mills, with only conditioning temperature and pellet diet L:D having greater contributions to energy use.

The use of pellet binders has been shown to be effective for improving pellet quality when soybean oil is added to broiler diets. A recent study by Abadi et al. (2019) evaluated the effects of adding 0, 1.5, or 3.0% soybean oil to corn-soybean meal-based finishing broiler diets, with and without bentonite (0, 1, or 2%) or calcium lignosulfonate (0, 0.5, or 1%) on pellet hardness, length, and durability index. Two common methods were used to evaluate pellet durability index, which included the Pfost tumbling box (PDIT) and the Holmen NHP100 tester (PDIH). The PDIT method was specifically designed to mimic feed transportation systems in the U.S., while the PDIH method is harsher (Winowski, 1998) and was designed to mimic feed delivery systems in Europe (Pope, 2016). The PDIT method has been shown to have a high association with actual percentage of fines in feed lines on farms than PDIH values obtained from the Holmen tester (Hancock, 2010: Fahrenholz, 2012), and some researchers have suggested that the Holmen tester is unreliable (Salas-Bringas et al., 2007; Singh et al., 2014).

Results from this study (Abadi et al., 2019) showed that as the dietary level of soybean oil increased without pellet binders, all pellet quality measures except PDIT decreased (Table 2). When increasing dietary levels of bentonite were added to the 1.5% soybean oil diets, PDIH and pellet harness of diets improved. However, increasing bentonite levels from 1 to 2% in the 3% soybean oil diets did not prevent a reduction in PDI. In fact, increasing soybean oil inclusion rate from 1.5% to 3% without pellet binders resulted

in a 12 percentage point decrease in PDIH. The addition of 0.5% calcium lignosulfonate (CaLS) to 1.5% soybean oil diets improved PDIH by 7 percentage points, but PDIH improved by 28 percentage points when added to the 3% soybean oil diet. Diets containing 3% soybean oil and 0.5% CaLS had the greatest pellet hardness and pellet length among all treatments. Based on these results, the optimal combination of PDIH, pellet hardness, and pellet length was when diets contained 3% soybean oil with 0.5% CaLS.

Table 2. *Effects of soybean oil inclusion rate and type and inclusion rate of pellet binders on pellet durability indices, hardness, and length in broiler finisher diets (adapted from Abadi et al., 2019).*

Soybean oil, %	Binder type	Binder, %	PDIT (Pfost)[1], %	PDIH (Holmen)[2], %	Pellet hardness[3], N	Pellet length[4], mg/pellet
0	None	0	94.7	59.2	32.5	111.0
0	Bentonite	2	96.0	82.9	40.6	123.2
1.5	None	0	94.5	69.0	31.5	111.9
1.5	Bentonite	1	94.7	74.1	40.2	114.4
1.5	Bentonite	2	95.3	80.4	45.2	113.7
1.5	CaLS	0.5	93.3	76.7	17.7	109.0
1.5	CaLS	1	94.9	78.7	9.5	126.9
3	None	0	94.5	56.9	24.1	144.6
3	Bentonite	1	95.3	65.7	33.3	106.0
3	Bentonite	2	89.7	22.0	24.3	87.0
3	CaLS	0.5	96.3	85.7	53.5	144.6
3	CaLS	1	91.7	38.4	31.0	96.4

[1]Pellet durability index (PDI) based on Pfost tumbling box.
[2]Pellet durability index (PDI) based on Holmen NHP100.
[3]Pellet hardness based on Brookfield CT3.
[4]Pellet length based on procedure from Winowiski (1995).

Similar to results reported by Abadi et al. (2019), Pope (2016) reported that increasing dietary soybean oil inclusion rate from 1.5% to 3% reduced PDIH by 21 percentage points. Furthermore, Pope (2016) reported a 22 percentage point increase in PDIH when 0.5% CaLS was added to a 3% soybean oil diet compared with the 11 percentage point increase when CaLS was added to a 1.5% soybean oil diet. Cavalcanti and Behnke (2005b) suggested that use of high dietary soybean oil inclusion rates reduces frictional heat by reducing compression forces and flow of plasticized material within the pellet diet orifice. Calcium lignosulfonate is a water-soluble powder that can penetrate the hydrophobic layer of feed particles to facilitate hydrogen bonding on the outer surface of pellets (Pope, 2016).

Pelleting has generally been shown to improve starch gelatinization, which contributes to increased digestibility of energy (Richert and DeRouchey, 2010; NRC, 2012). Some researchers have suggested that increasing dietary soybean oil content reduces starch gelatinization (Cavalcanti and Behnke, 2005b), while others have shown that starch gelatinization is quadratically increased when up to 3.5% soybean oil is added to diets (Muramatsu et al., 2014). However, other researchers have suggested that starch gelatinization is not a major factor contributing to pellet quality (Moritz et al., 2003: Svihus et al., 2004; Zimonja, 2009). Zimonja et al. (2007) showed that soybean oil creates layer-barrier problems which reduced gelatinization of starch granules and limits steam penetration during the pelleting process.

CONCLUSIONS

The addition of soybean oil to mash diets has been consistently shown to substantially reduce dust in feed mills and confinement animal facilities, which has beneficial effects on respiratory health of humans and animals. In general, increasing diet inclusion rates of soybean oil in swine and poultry diets reduces pellet durability, but the magnitude of this effect is dependent on the steam conditioning temperature used during the pelleting process. The addition of a pellet binder, such as 0.5% calcium lignosulfonate, can be effective in improving pellet quality in broiler diets containing up to 3% soybean oil. Acceptable pellet durability can also be achieved by adding 1% oil to the mixer before pelleting, and adding the remaining oil after pelleting. However, the disadvantages of adding greater amounts of soybean oil to the diet before pelleting is the potential risk of reduced nutrient digestibility and vitamin potency losses because fats or oils may decrease friction and heat generated between the pellet die and mash feed. The lubricating effect of soybean oil during the pelleting process is one of the main factors associated with reduced energy consumption of pellet mills.

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Chapter

08

Feeding Applications of U.S. Soybean Oil in Swine Diets

INTRODUCTION

Numerous research studies have been conducted during the past several decades that have shown multiple benefits of using U.S. soybean oil in swine diets compared with other commercially available fats and oils. Swine nutritionists around the world consider U.S. soybean oil as the "gold standard" because of its abundant supply, consistent quality, high energy content, and competitive price. The use of high quality U.S. soybean oil in growing pig diets provides an "extra caloric" effect, which means that the percentage improvement in feed conversion exceeds the percentage increase in energy content of the diet (Campbell, 2005).

In addition to the high energy content of high quality U.S. soybean oil, it been shown to provide additional value-added benefits such as reducing dust levels in swine confinement facilities to improve respiratory health of pigs and people. In addition, although soybean oil contains a high concentration of polyunsaturated fatty acids (PUFA), which reduces pork fat firmness when fed to growing-finishing pigs, it also increases the PUFA content in pork products, which have been shown to provide human health advantages. Consumption of meat products high in saturated fats have been associated with the potential risk of atherosclerosis and cardiovascular disease in humans. Therefore, opportunities exist to produce more "heart healthy" pork products if U.S. soybean oil is added to growing-finishing pig diets.

Another value-added benefit of U.S. soybean oil involves its beneficial effects on reproductive performance of sows. It is well documented that the use of U.S. soybean oil increases caloric intake of sows, especially under heat stress conditions, while also improving milk fat content and litter growth rate. Furthermore, soybean oil contains high concentrations of both essential fatty acids (linoleic and linolenic acid), which are needed for optimal fertility. In fact, results from recent research studies have shown that modern sows are typically consuming diets deficient in essential fatty acids, especially as they increase in age or parity. This negative essential fatty acid balance can easily be corrected by adding adequate amounts of U.S. soybean oil to lactation diets to reduce the weaning-to-estrus interval and improve subsequent litter size. Therefore, U.S. degummed soybean oil should be considered as the preferred supplemental lipid source for use in sow diets because it is the only commercially available lipid source that contains high concentrations of both linoleic and linolenic acids.

DIGESTIBLE AND METABOLIZABLE ENERGY CONTENT OF SOYBEAN OIL

One of the greatest challenges in capturing the full value of any feed ingredient, including U.S. degummed soybean oil, is to use accurate energy values for the source used in swine diet formulations. Like all commodity feed ingredients, there is substantial variability in digestible energy (DE), metabolizable energy (ME), and net energy (NE) estimates among published studies. This high variability is caused by many factors including the source, diet inclusion rate, age of pig, type of basal diet used, and extent of oxidation of the soybean oil source evaluated in these studies.

Digestible energy and ME are commonly used to formulate swine diets despite their inherent inaccuracies of not accounting for heat increment losses from digestion and metabolism, which are taken into account when using the net energy (NE) system (Velayudhan et al., 2015; NRC, 2012). Many swine nutritionists use published DE and ME values for soybean oil from the U.S (NRC, 2012), France (Sauvant et al., 2004), or Brazil (Rostagno, 2017). It is rare for researchers to identify country of origin or specific sources of lipids evaluated in energy determination or animal performance studies. As a result, it is not surprising that it is often difficult to differentiate DE and ME values for U.S. soybean oil from other sources,

which may partially explain why ME estimates vary from 7,906 kcal/kg (France; Sauvant et al., 2004) to 8,300 kcal/kg (Brazil; Rostagno, 2017), to 8,574 (U.S.; NRC, 2012). In addition, the composition of lipid sources, including soybean oil, may change over time due to genetic improvements in soybean breeding and oil extraction processes, which may affect the difference in DE and ME content reported by historical experiments compared with more recent studies. Therefore, it seems prudent to focus more attention on recently published DE and ME values rather than those reported from studies 10 or more years ago.

Furthermore, it is generally accepted that DE and ME content of lipid sources vary depending on age of the pig and diet inclusion rate. However, these responses are not always consistent. For example, despite numerical increases in DE and ME content of soybean oil with increasing diet inclusion rates, these differences were shown to not be significantly different (Su et al., 2015). Instead, Su et al. (2016) indicated that DE and ME values were affected to a greater extent by diet inclusion rate, but not by experimental basal diet composition. However, it is important to consider that despite the greater energy values for soybean oil reported at inclusion rates greater than 5%, it is unusual to add more than 5% of any lipid source to swine diets. Therefore, attention should be focused on using DE and ME values derived for a specific pig body weight range at diet inclusion rates of 5% or less. In addition, it also generally assumed that ME content of lipids is 98% of DE content (van Milgen et al., 2001; NRC, 2012), but this relationship can also vary among reported results.

A summary of recently published DE and ME values for swine are shown in **Table 1.** Note that DE content ranges from 7,977 to 9,979 kcal/kg, and ME content ranges from 7,906 to 8,868 kcal/kg for soybean oil. This creates a dilemma for nutritionists and feed formulators when deciding on which DE or ME value to assign to U.S. soybean oil for accurate diet formulation. Using a conservative, low estimate may limit the use of soybean oil in least cost formulations, whereas using the maximum reported value may overestimate the actual ME content of the soybean oil source used, resulting in suboptimal performance responses. Another approach that has been developed, is to potentially use DE and ME prediction equations to dynamically estimate the DE and ME content of a specific soybean oil source, rather than rely on using static published "book values". If accurate energy prediction equations were developed, they eliminate the challenge of accurately estimating DE, ME, and NE content of the U.S. soybean oil source being used. However, as discussed in a subsequent section of this chapter, most of the current published energy prediction equations either greatly overestimate or underestimate actual DE and ME content of lipid sources, including soybean oil.

Table 1. *Published estimates of DE and ME content of soybean oil in swine diets*

Pig body weight	Diet inclusion rate	DE, kcal/kg	ME. kcal/kg	Reference
13 kg	5%	8,993 – 9,038	8,813 – 8,856	Kellner and Patience (2017)
50 kg	5%	8,181 – 9,049	8,017 – 8,868	Kellner and Patience (2017)
38 kg	4, 6, 8, 10%	4% = 8,243 6% = 8,419 8% = 8,775 10% = 8,911	4% = 7,966 6% = 8,190 8% = 8,422 10% = 8,797	Su et al. (2015)
34 kg	5 and 10% using two different basal diets	Corn-soybean meal 5% = 8,357 10% = 8,410 Corn starch casein 5% = 8,054 10% = 8,410	Corn-soybean meal 5% = 8,099 10% = 8,854 Corn starch casein 5% = 7,896 10% = 8,319	Su et al. (2016)
19 kg	7.13%	9,979	-	Kerr et al. (2018)
10 kg	6.7%	8,567	8,469	Kerr et al. (2009)
15 kg	10%	8,315	8,368	Kerr and Shurson (2016)
-	-	8,749	8,574	NRC (2012)
-	-	7,977	7,906	Sauvant et al. (2004)
-	-	8,600	8,300	Rostagno (2017)

NET ENERGY CONTENT OF SOYBEAN OIL

The use of DE and ME systems are not as accurate as the NE system for assessing the actual productive energy value of lipids and other feed ingredients (de Lange and Birkett, 2005). However, like DE and ME values, Published values for NE content of soybean oil and other fats and oils are highly variable among studies (van Heugten et al., 2015). Kil et al. (2011) determined the NE value of soybean oil using a comparative slaughter technique, but average NE values reported (4,822 kcal/kg) were substantially less than those reported by Sauvant et al. (2004; 7,110 kcal/kg) and NRC (2012; 7,545 kcal/kg). This discrepancy in NE determination for lipids using the comparative slaughter technique is likely due to the values of NE attributed to maintenance energy requirements (Noblet et al., 1994), and are likely much greater for pigs housed in practical production conditions (Verstegen et al., 2001). Therefore, use of indirect calorimetry appears to provide more accurate NE estimates of lipids for swine. Dietary lipids have low heat increment during digestion and metabolism compared with other nutritional components (Kleiber, 1961; Kronfeld, 1996). Furthermore, when feeding diets containing low inclusion rates of lipids that contain high concentrations of unsaturated fatty acids, a substantial proportion of these fatty acids are deposited directly into adipose tissue which leads to reduced heat production and a greater NE value (Leveille et al., 1975; Black, 1995). In contrast, when feeding diets containing high inclusion rates of unsaturated lipid sources, a greater proportion of these fatty acids are used as energy sources and released as heat. As a result, diet inclusion rate of lipids, including soybean oil, affects NE content (Stahly, 1984; Allee et al., 1971; 1972). In general, it is assumed that the ME content of lipids is 98% of DE content, and NE content is 88% of ME content (van Milgen et al., 2001; NRC, 2012).

Table 2. *Estimates of NE content of soybean oil in swine diets from recent publications.*

Pig body weight	Diet inclusion rate	NE, kcal/kg	Reference
22 kg	5 or 10%	5% = 4,561 10% = 4,781	Kil et al. (2011)
84 kg	5 or 10%	5% = 5,585 10% = 4,578	Kil et al. (2011)
31 kg	5 or 10%	5% = 7,989 10% = 8,132	Li et al. (2018)
13 kg	5%	7,756 – 7,795	Kellner and Patience (2017)
50 kg	5%	7,055 – 7,804	Kellner and Patience (2017)
-	-	7,545	NRC (2012)
-	-	7,117	Sauvant et al. (2004)
-	-	7,364	Rostagno (2017)

ENERGY PREDICTION EQUATIONS

Several DE, ME, and NE prediction equations have been developed for estimating energy content of various fats and oils. However, it is important to realize that if prediction equations are used to estimate energy content of fats and oils, they should be derived from experiments that have directly determined DE, ME, or NE content, and not from studies that evaluated other feed ingredients. Theoretically, it is often assumed that energy prediction equations derived from a lipids with diverse fatty acid profiles should result in reasonably accurate predictions when compared with energy values directly determined from in vivo experiments. However, results from recent studies have shown that this is generally not the case. There may be at least two explanations for this. First, most energy prediction equations were derived without consideration of the extent of oxidation of the lipids evaluated. Lipid oxidation typically reduces energy content of lipids, but not always (Liu et al., 2014; Lindblom et al. 2018). Second, it is important to realize that although prediction equations may accurately estimate DE, ME, or NE content of lipid sources in an experiment from which they were derived, they may not result in accurate predictions when applied to lipid sources and composition not included in the original data set.

For example, Kerr et al. (2018) determined that the DE content (9,979 kcal/kg) of soybean oil for 19 kg pigs was greater than all other fats and oils evaluated (butter fat, canola oil, coconut oil, fish oil, flaxseed oil, lard, olive oil, palm oil, and tallow), with DE values ranging from 8,071 to 9,606 kcal/kg DE. However, when the Powles et al. (1995) and Kellner and Patience (2017) DE prediction equations were used to estimate the DE content of soybean oil, the DE content was underestimated to contain 8,944 kcal/kg and 8,769 kcal/kg, respectively.

Rosero et al. (2015) determined that the soybean oil source evaluated in their study contained 9,086 kcal/kg DE. When they used the chemical composition of this soybean oil source and their derived DE prediction equation, the predicted DE content was estimated to be 8,900 kcal/kg (difference of 186 kcal/kg), which was reasonably similar to the actual in vivo DE value **(Table 4).** However, when they used the Powles et al. (1995) DE equation for this same soybean oil source, the predicted DE content was 8,805 kcal/kg, which was -281 kcal/kg less than observed **(Table 4).** Therefore, caution should be used when selecting and using energy prediction equations to estimate DE, ME, and NE content of U.S. soybean oil.

Table 3. *Published DE, ME, and NE prediction equations for lipids fed to swine.*

Pig body weight	Equation	R^2	Reference
19 kg	DE (kcal/kg) = 10,267 – (110.3 × FFA, %) – (41.8 × C16:0, %) – (39.7 × C18:0, %) – (98.0 × U:S) + (6.4 × iodine value)	0.97	Kerr et al. (2018)[1]
13 kg	DE (Mcal/kg) = 9.363 – (0.097 × FFA, %) – (0.016 × n-6:n-3) – (1.24 × C20:0, %) – (5.054 × insoluble impurities, %) + (0.014 × C16:0, %)	0.81	Kellner and Patience (2017)[2]
	ME (Mcal/kg) = 9.176 – (0.095 × FFA, %) – (0.016 × n-6:n-3) – (1.215 × C20:0, %) – (4.953 × insoluble impurities, %) + (0.014 × C16:0, %)	0.81	Kellner and Patience (2017)
	NE (Mcal/kg) = 8.075 – (0.093 × FFA, %) – (0.014 × n-6:n-3) – (1.07 × C20:0, %) – (4.359 × insoluble impurities, %) + (0.013 × C16:0, %)	0.81	Kellner and Patience (2017)
	DE (kcal/kg) = 37.89 – (0.0051 × FFA, g/kg) – $8.20^{(-0.515 \times U:S)}$/0.004184	-	Powles et al. (1995)
50 kg	DE (Mcal/kg) = 8.357 + (0.189 × U:S) – (0.195 × FFA, %) – (6.768 × C22:0, %) + (0.024 × PUFA, %)	0.81	Kellner and Patience (2017)
	ME (Mcal/kg) = 8.19 + (0.185 × U:S) – (0.191 × FFA, %) – (6.633 × C22:0, %) + (0.023 × PUFA, %)	0.81	Kellner and Patience (2017)
	NE (Mcal/kg) = 7.207 + (0.163 × U:S) – (0.168 × FFA, %) – (5.836 × C22:0, %) + (0.021 × PUFA, %)	0.81	Kellner and Patience (2017)
	DE (kcal/kg) = 36.898 – (0.0046 × FFA, g/kg) – $7.33^{(-0.906 \times U:S)}$/0.004184		Powles et al. (1995)
Lactating sows	DE (kcal/kg) = 8,381 – (80.6 × FFA, %) + (0.4 × FFA^2, %) + (248.8 × U:S) – (28.1 × $U:S^2$) + (12.8 × FFA, % × U:S)	0.74	Rosero et al. (2015)[3]

[1]Equation derived from determining DE content and chemical composition of butter fat, canola oil, coconut oil, fish oil, flaxseed oil, lard, olive oil, palm oil, soybean oil, and tallow.
[2]Equations derived from determining DE, ME, and NE content and chemical composition of an animal-vegetable blend, canola oil, two source of choice white grease, coconut oil, two sources of corn oil, fish oil, flax oil, palm oil, poultry fat, two sources of soybean oil, and tallow.
[3]Equation derived from determining DE and chemical composition of choice white grease, choice white grease acid oil, soybean oil, soy-cotton acid oil, animal-vegetable blend

Table 4. *Comparison of actual vs. predicted DE (Mcal/kg) of soybean oil using (Powles et al., 1995) and Kellner and Patience (2017) equations*

	Actual DE	Powles et al. (1995) predicted DE	Kellner and Patience (2017) predicted DE
13 kg BW			
Soybean oil source A	9.04	8.81	8.95
Soybean oil source B	8.99	8.81	8.97
50 kg			
Soybean oil source A	9.05	8.81	8.66
Soybean oil source B	8.18	8.81	8.71

Table 5. *Effect of dietary form (intact vs. extracted) of soybean oil on dry matter, energy, lipid, and nitrogen digestibility in weaned pigs (adapted from Adams and Jensen, 1984).*

Measure	Intact soybean oil in roasted soybeans	Extracted soybean oil
Apparent total tract digestibility, %		
Dry matter	83.0[b]	92.8[a]
Gross energy	78.2[b]	93.0[a]
Lipid	72.1[b]	96.9[a]
Nitrogen	73.2[b]	87.0[a]
Metabolizable energy, %	75.1[b]	90.1[a]
Nitrogen retained, %	52.7[b]	56.9[a]

[a,b] Means with uncommon superscripts are different (P < 0.005)

Table 6. *Apparent ileal digestibility of dry matter, crude protein, and amino acids in diets containing 0% or 5% soybean oil or 5% choice white grease (adapted from Kil et al., 2011)*

Measure, %	Control	5% soybean oil	5% choice white grease
Dry matter	69.0	71.7	71.0
Crude protein	85.5	84.3	83.7
Arginine	85.8[a]	87.3[b]	87.4[b]
Histidine	81.0[x]	83.2[xy]	83.5[y]
Isoleucine	77.2[x]	79.7[y]	79.5[xy]
Leucine	81.5[a]	84.0[b]	83.5[ab]
Lysine	77.0	79.7	79.0
Methionine	82.7	84.7	84.3
Phenylalanine	80.1[x]	82.6[y]	82.0[xy]
Threonine	69.2	71.3	70.2
Tryptophan	81.6	81.9	83.0
Valine	74.6[a]	78.0[b]	77.9[b]
Total indispensable	79.2[x]	81.6[y]	81.2[xy]

[a,b]Values within row lacking common superscripts are different (P < 0.05).
[x,y]Values within row lacking common superscripts are different (0.05 < P < 0.10).

DIFFERENCES IN LIPID DIGESTIBILITY WHEN FEEDING FULL-FAT SOYBEANS COMPARED WITH EXTRACTED SOYBEAN OIL

During the past several decades, there has been considerable interest in feeding roasted or extruded full-fat soybeans to swine, as a combined source of supplemental lipids and amino acids. However, one of the potential limitations of using heat-processed full-fat soybeans in swine diets is to ensure that adequate thermal treatment is applied during these processes to effectively reduce the anti-nutritional factors (e.g. trypsin inhibitors) that cause reduced amino acid digestibility. A second limitation is that the digestibility of soybean oil from intact heat processed soybeans is less than in extracted soybean oil.

Adams and Jensen (1984) compared the energy content and nutrient digestibility of diets containing roasted soybeans by feeding isocaloric and isonitrogenous diets containing the same amount of extracted soybean oil in 6 kg pigs. Diets that contained extracted soybean oil had significantly greater dry matter, energy, lipid, and nitrogen digestibility, and nitrogen retention compared with pigs fed diets containing an equivalent amount of soybean oil from roasted full-fat soybeans **(Table 5).** Similarly, Agunbiade et al. (1992) compared feeding diets containing increasing concentrations (4, 8, or 12%) of soybean oil from extruded full-fat soybeans, or soybean meal and extracted soybean oil, to growing pigs on dietary DE content. These researchers reported lower DE content in the extruded full-fat soybean diet compared with the diets containing a combination of extracted soybean oil and soybean meal. Furthermore, these responses were linearly related to diet inclusion rate, but pig body weight (32 to 70 kg) had no effect. These results indicate that adding extracted soybean oil to swine diets greatly improves energy digestibility compared with feeding diets containing the same amount of soybean oil from heat-processed full fat soybeans. Furthermore, using extracted soybean oil and soybean meal eliminates the concern of adequate heat treatment of full-fat soybeans to insure optimal amino acid digestibility and growth performance.

EFFECTS OF SOYBEAN OIL ON AMINO ACID DIGESTIBILITY

Two studies has been conducted to demonstrate that adding 5% soybean oil or choice white grease to growing pig diets (containing corn, soybean meal, and 20% corn DDGS) increases amino acid digestibility (Kil et al., 2011). The apparent ileal digestibility of indispensable amino acids (arginine, histidine, isoleucine, leucine,

phenylalanine, and valine) and several dispensable amino acids were improved by adding either soybean oil or choice white grease to the diet **(Table 6).** The addition of supplemental lipids to swine diets has been shown to reduce the rate of gastric emptying (Low et al., 1985) and decrease the rate of passage of digesta (Valaja and Siljander-Rasi, 2001), which likely increases the time for more complete protein digestion and amino acid absorption (Li and Sauer, 1994). Albin et al. (2001) also observed improvements in apparent ileal amino acid digestibility of leucine and arginine when growing pig (78 kg body weight) diets were supplemented with 2% soybean oil. These researchers also observed linear improvements in apparent ileal digestibility of serine, histidine, arginine, tyrosine, and leucine with increasing supplementation levels (0, 1, and 2%) of soybean oil to the diets. However, although these improvements in amino acid digestibility from feeding diets containing soybean oil are positive, the relatively small magnitude of improvement does not warrant making diet formulation adjustments.

EFFECTS OF SOYBEAN OIL ON MINERAL DIGESTIBILITY

There have been only a few studies conducted to evaluate mineral digestibility of diets containing soybean oil (Steiner et al., 2006; Gonzalez-Vega et al., 2015; Merriman et al., 2016). Studies by Steiner et al. (2006) and Gonzalez-Vega et al. (2015) reported that feeding diets containing soybean oil to pigs had no effect of calcium and phosphorus digestibility. However, a more recent study conducted by Merriman et al. (2016) showed that the addition of 7% soybean oil to diets for 16 kg pigs improved the apparent total tract digestibility (ATTD) of several minerals compared with feeding other lipid sources (Table 7). The addition of soybean oil, corn oil, and palm oil improved dry matter, ether extract (lipid), and acid hydrolyzed ether extract (AEE) digestibility compared with feeding animal fats (tallow, choice white grease) and the basal diet. In fact, soybean oil had the highest numerical ATTD of these digestibility measures. Furthermore, diets containing 7% soybean oil, corn oil, palm oil, and tallow had improved calcium, phosphorus, and sulfur digestibility compared to feeding choice white grease or the basal diet. Again, feeding the soybean oil diet resulted in the highest numerical ATTD of calcium and phosphorus compared with feeding the other lipid sources. However, there were no differences in ATTD of magnesium, sodium, potassium, manganese, or zinc among diets containing the various lipid sources. These results suggest that feeding supplemental dietary lipids does not reduce digestibility of calcium or lipid, and that soybean oil had the greatest effect on improving dry matter, lipid, calcium, and phosphorus digestibility among the lipid sources evaluated..

Table 7. *Apparent total tract digestibility of dry matter, ether excract (EE), acid hydrolyzed ether extract (AEE), and macro- and micromineral in diets containing 7% tallow, choice white grease (CWG), palm oil, corn oil, or soybean oil to young pigs (adapted from Merriman et al., 2016).*

ATTD, %	Basal	Tallow	CWG	Palm oil	Corn oil	Soybean oil
Dry matter	89.79^{bc}	90.68^{ab}	89.25^{c}	90.88^{ab}	90.73^{ab}	91.59^{a}
EE	29.62^{c}	81.59^{ab}	77.77^{b}	83.23^{a}	84.59^{a}	86.15^{a}
AEE	39.75^{c}	81.17^{ab}	79.05^{b}	82.77^{ab}	82.84^{ab}	85.17^{a}
Calcium	51.65^{b}	65.13^{a}	54.07^{b}	66.07^{a}	67.47^{a}	71.71^{a}
Phosphorus	52.06^{b}	62.00^{a}	53.52^{b}	61.06^{a}	59.80^{a}	62.98^{a}
Magnesium	25.62	24.73	23.53	26.94	30.91	35.37
Sodium	90.40	90.00	90.66	90.69	91.30	91.95
Potassium	76.68	74.25	72.60	77.37	73.89	79.17
Sulfur	81.70^{b}	83.75^{a}	81.31^{b}	83.98^{a}	84.03^{a}	83.40^{a}
Manganese	14.70	20.59	10.96	21.43	22.49	19.38
Zinc	13.51	11.14	11.74	13.68	17.00	12.29

^{a,b,c}**Means with uncommon superscripts are different (P < 0.05).**

Table 8. *Effect of dietary level of soybean oil on overall growth performance (day 0 to 35 postweaning) in nursery pigs (adapted from Adeola et al., 2013.*

Measure	1% soybean oil	3% soybean oil	5% soybean oil
Body weight, kg			
Day 0	6.76	6.72	6.74
Day 35	24.36	24.02	24.02
ADG, g	501	490	500
ADFI, g[1]	697	669	661
G:F[1]	724	737	747

[1]**Linear effect of dietary soybean oil inclusion level (P < 0.001).**

Table 9. *Effect of dietary level of soybean oil on apparent total tract digestibility of dry matter, nitrogen, lipid, and energy from day 7 to 21 and day 22 to 35 in nursery pigs (adapted from Adeola et al., 2013).*

Measure	1% soybean oil	3% soybean oil	5% soybean oil
Diet digestibility - day 7 to 21			
Dry matter, %	88.95	88.99	90.01
Nitrogen, %	89.06	87.73	89.87
Lipid[1], %	68.08	75.08	79.63
Energy digestibility, %	89.97	90.19	90.87
Energy metabolizability, %	85.03	85.78	86.78
ME[1], kcal/kg	3,787	3,918	4,061
Diet digestibility - day 22 to 35			
Dry matter, %	85.07	85.43	85.94
Nitrogen, %	82.02	84.22	84.21
Lipid[1], %	72.38	80.33	86.89
Energy digestibility, %	85.34	86.17	86.61
Energy metabolizability, %	82.05	83.05	83.26
ME[1], kcal/kg	3,473	3,647	3,763

[1]**Linear effect of dietary soybean oil inclusion level (P < 0.001).**

SOYBEAN OIL IN WEANED PIG DIETS

A multi-university (n = 9) study was conducted to re-evaluate growth performance and energy utilization responses of nursery pigs fed increasing dietary levels (1, 3, and 5%) of U.S. soybean oil (Adeola et al., 2013). Diets were fed in 3-phases (phase 1 = day 0 to 7, phase 2 = day 8 to 21, phase 3 = day 22 to 35), and were formulated to maintain a constant calorie to lysine ratio within each phase. The energy values for U.S. soybean oil were obtained from NRC (2012). A high quality U.S. soybean oil source was used and contained 94.6% total fatty acids, 0.02% moisture, 0.01% insolubles, 0.49% unsaponifiables, and 1.13% free fatty acids). A summary of growth performance and energy utilization efficiency of diets containing U.S. soybean oil in this multi-university study are shown in **Table 8.** Increasing dietary inclusion levels of U.S. soybean oil had no effect on body weight of pigs on day 35 of the feeding period, and overall average daily gain (ADG). However, as expected, adding increasing dietary levels of soybean oil to nursery diets linearly reduced average daily feed intake (ADFI) and linearly improved Gain:Feed (G:F). Furthermore, increasing dietary levels of U.S. soybean oil from 1% to 5% had no effect on dry matter, nitrogen, and energy digestibility and metabolizability, but linearly increased ME content and lipid digestibility from day 7 to 21 and day 22 to 35 in nursery pigs **(Table 9).** When calculating the efficiency of energy use for body weight gain of nursery pigs fed diets with increasing levels of U.S. soybean oil, there were no difference from day 7 to 21 and day 22 to 35 post-weaning **(Table 10).** These results indicate that the energy values for U.S. soybean oil obtained from NRC (2012) are reasonably accurate.

Jung et al. (2003) determined the effects of feeding diets containing 5% corn oil, soybean oil, tallow, and fish oil to 5.8 kg weaned pigs on growth performance, nutrient digestibility, serum lipid components, and intestinal morphology over a 28-day feeding period. Growth rate was greater, and Feed:Gain (F:G) was less for pigs fed the corn oil and soybean oil supplemented diets compared with this fed tallow and fish oil supplemented diets **(Table 11).** Gross energy, dry matter, ether extract, and ash digestibility of corn oil and soybean oil supplemented diets were similar, but pigs fed the diet containing soybean oil had greater crude protein digestibility than those fed the corn oil, tallow, and fish oil diets **(Table 11).** Vegetable oils such as soybean oil contain a greater proportion of unsaturated fatty acids relative to saturated fatty acids, which results in greater apparent ether extract digestibility compared with animal fat sources (Cera et al., 1988b, 1989a, 1990b; Li et al., 1990). The greater digestibility of soybean oil is due to an increased ability of

unsaturated fatty acids to partition in the micellar phase during digestion and absorption than for saturated fatty acids (Freeman, 1969). Pigs fed corn oil, soybean oil, and tallow had similar villi height in the duodenum and jejunum, which was greater than pigs fed fish oil. However, villi height in the ileum was greater for pigs fed the corn oil diets compared with those fed soybean oil, tallow or fish oil diets **(Table 11).** It has been suggested that a reduction in villi height may decrease total luminal villus absorptive area, which may subsequently result in suboptimal digestive enzyme activity and absorption of nutrients (Cera et al., 1988a). Extreme caution should be used when assuming this hypothetical association. In the animal science field, it is widely accepted that longer villi are associated with greater absorptive capacity and thus, longer villi are often considered as an indicator improvement in gut health. However, there is not a single published study that shows that intestines with longer villi indeed absorb more nutrients. Moreover, greater intestinal villi height and deeper crypts may infer that the GI tract may be heavier, which is undesirable relative to pig growth performance. It would be more useful to demonstrate more villi per length of intestine, which implies even larger absorptive capacity even if villi do not change in height, but this measurement has been rarely reported in the scientific literature. Therefore, interpretation of changes in villi height and crypt depth needs to be supported by functional measurements. Currently, the optimal villus height, crypt depth, and the ideal proportion of these measures that should be present in each section of the pig's intestine at different ages to support optimal growth are unknown. Therefore, unless there is clear damage to the tissue or the villi are severely blunted, changes of intestinal morphology do not provide evidence of gut health.

Table 10. *Effect of dietary level of soybean oil on efficiency of energy use for body weight (BW) gain in nursery pigs from day 7 to 21 and day 22 to 35 post-weaning (adapted from Adeola et al., 2013).*

Measure	1% soybean oil	3% soybean oil	5% soybean oil
Day 7 to 21			
BW gain/DE intake, kg/kcal	192	189	188
BW gain/ME intake, kg/kcal	203	199	198
BW gain/NE intake, kg/kcal	282	276	269
BW gain/ME intake above maintenance, kg/kcal	329	325	319
BW gain/NE intake above maintenance, kg/kcal	455	451	435
Day 22 to 35			
BW gain/DE intake, kg/kcal	186	187	184
BW gain/ME intake, kg/kcal	194	191	191
BW gain/NE intake, kg/kcal	264	264	259
BW gain/ME intake above maintenance, kg/kcal	287	286	284
BW gain/NE intake above maintenance, kg/kcal	391	390	385

Table 11. *Effect of adding 5% of various lipid sources to weaned pig diets on growth performance, apparent dietary energy and nutrient digestibility, and intestinal morphology (adapted from Jung et al., 2003).*

Measurement	Corn oil	Soybean oil	Tallow	Fish oil
Growth performance (0-28 days)				
ADG, g	390^{a}	387^{a}	346^{b}	336^{b}
ADFI, g	545	559	535	513
F:G	1.40^{b}	1.44^{ab}	1.55^{a}	1.53^{ab}
Apparent digestibility, %				
Gross energy	86.4^{a}	86.1^{ab}	85.9^{b}	85.8^{b}
Dry matter	86.9	86.8	86.7	86.8
Crude protein	82.2^{b}	83.3^{a}	81.8^{b}	82.0^{b}
Ether extract	83.0^{a}	82.7^{ab}	78.5^{c}	78.8^{bc}
Ash	59.5^{b}	60.9^{b}	63.8^{a}	62.2^{ab}

Continuation Table 11. *Effect of adding 5% of various lipid sources to weaned pig diets on growth performance, apparent dietary energy and nutrient digestibility, and intestinal morphology (adapted from Jung et al., 2003).*

Measurement	Corn oil	Soybean oil	Tallow	Fish oil
Intestinal morphology				
Duodenum				
Villi height, µm	512[a]	518[a]	492[a]	398[b]
Crypt depth, µm	170	201	216	170
Jejunum				
Villi height, µm	541[a]	411[ab]	482[ab]	365[c]
Crypt depth, µm	168[a]	159[ab]	160[ab]	129[b]
Ileum				
Villi height, µm	464[a]	397[b]	370[b]	363[b]
Crypt depth, µm	158	127	146	150

[a,b,c] **Means with uncommon superscripts are different (P < 0.05).**

SOYBEAN OIL IN GROWING-FINISHING PIG DIETS

Kil et al. (2013) determined the effects of feeding 0 or 8% U.S. soybean oil diets to growing (27 kg) and finishing (87 kg) pigs on growth performance and retention of energy, protein, and lipids. As shown in **Tables 12 and 13,** there was a trend for improved ADG, dietary DE content, and digesta-free body weight (BW) when 8% soybean oil was added to the diets. These improvements were likely a result of significant improvements in ATTD of acid hydrolyzed ether extract digestibility and gross energy (GE) by feeding the 8% soybean oil diets compared with feeding the control diet. However, feeding the 8% soybean oil diets had no effects on ADFI, G:F, or retention of energy, protein, and lipids.

Table 12. *Effects of feeding diets containing 0% or 8% U.S. soybean oil to growing and finishing pigs on growth performance and dietary energy and nutrient digestibility (adapted from Kil et al., 2013)*

Measure	Growing pigs		Finishing pigs	
	0% soybean oil	8% soybean oil	0% soybean oil	8% soybean oil
Initial BW, kg	27.3	27.3	85.3	86.2
Final BW, kg	54.3	55.9	129.3	133.7
ADG[1], kg	0.96	1.02	1.26	1.36
ADFI, kg	2.06	2.19	3.89	3.80
G:F	0.47	0.47	0.33	0.36
Crude protein ATTD, %	77.2	76.2	74.2	76.4
Acid hydrolyzed ether extract ATTD[2], %	47.5	70.1	42.9	67.9
GE ATTD[2], %	80.9	81.9	82.4	84.3
Diet DE[1], kcal/kg	3,067	3,394	3,134	3,455

[1]**Trend (P < 0.12) for a soybean oil improvement.**
[2]**Soybean oil improvement (P < 0.05)**

Table 13. *Effects of feeding diets containing 0% or 8% U.S. soybean oil to growing and finishing pigs on carcass composition and retention of energy, protein, and lipids (adapted from Kil et al., 2013)*

Measure	Growing pigs		Finishing pigs	
	0% soybean oil	8% soybean oil	0% soybean oil	8% soybean oil
BW[1], kg	51.5	53.3	125.6	130.0
HCW, kg	41.9	43.3	105.2	109.0
Dressing percentage, %	81.4	81.3	83.7	83.8
Digesta-free BW[1], kg	49.5	51.3	124.4	128.9
Total protein, kg/pig	8.5	8.5	19.5	19.6
Total lipids, kg/pig	6.2	7.3	33.9	34.3
Total energy, Mcal/pig	107.2	120.5	428.5	444.6
Protein retained, g/d	143.3	146.5	174.1	173.1
Lipid retained, g/d	143.2	182.4	506.3	511.0
Energy retained, Mcal/d	2.3	2.7	5.8	6.2

[1]**Trend (P < 0.12) for a soybean oil improvement.**
[2]**Soybean oil improvement (P < 0.05).**

Benz et al. (2011) compared growth performance and carcass characteristics of growing-finishing pigs fed diets containing 5% choice white grease or 5% U.S. soybean oil **(Table 14).** Pigs fed the soybean oil diet tended to have greater ADG compared with pigs fed the choice white grease diet, but there were no difference in ADFI or Gain:Feed between dietary treatments. Feeding the choice white grease diets improved carcass yield compared with feeding soybean oil, but there were no differences in backfat thickness, loin depth, or percentage carcass lean between dietary treatments. However, feeding the soybean oil diets substantially increased jowl fat and backfat iodine value (unsaturated:saturated fatty acid content) compared with feeding the choice white grease diets. An increase in pork fat iodine value indicates a reduction in pork fat firmness, which may reduce shelf life stability and consumer preference in some markets.

Table 14. *Growth performance and carcass characteristics of pigs fed corn-soybean meal diets containing no supplemental lipid (control), 5% choice white grease, or 5% soybean oil over a 82-day feeding period (adapted from Benz et al., 2011)*

Measure	Control	5% Choice white grease	5% Soybean oil
Growth performance			
ADG, kg	0.99	1.04^{x}	1.07^{y}
ADFI, kg	3.15	2.96	3.11
G:F	0.35	0.38	0.39
Carcass characteristics			
Hot carcass weight, kg	90.6	94.3	95.9
Yield, %	72.5	73.3^{a}	73.1^{b}
Last-rib backfat, mm	24.4	22.4	26.4
10th-rib backfat, mm	17.8	17.8	20.1
Loin depth, mm	56.4	60.2	59.9
Carcass lean, %	54.5	55.2	53.7
Jowl fat iodine value, g/100 g	67.1	71.5^{a}	82.0^{b}
Backfat iodine value, g/100 g	63.3	68.8^{a}	84.3^{b}

^{a,b}**Means with uncommon superscripts are different (P < 0.05).**
^{x,y}**Means with uncommon superscripts are different (P < 0.07).**

The most recent study to evaluate the use of U.S. soybean oil in growing-finishing swine diets was conducted by Penner et al. (2018). The objective of this study was to compare growth performance, carcass characteristics, and the ratio of polyunsaturated to saturated fatty acids in pork meat for improved human nutrition. Results from numerous human nutrition studies have suggested that consumption of diets containing increasing amounts of saturated fats can lead to hypercholesterolemia, development of atherosclerosis, and greater risk of coronary heart disease risk. However, consumption of diets containing polyunsaturated fatty acids instead of saturated fats have been shown to decrease this risk. Therefore, growing-finishing pigs were fed corn-soybean meal diets containing either choice white grease (saturated fat source) or soybean oil (polyunsaturated oil source) at increasing levels of total caloric intake (0, 10, 20, 30, or 40% of total caloric intake). Growth performance results are shown in **Table 15.** There were no differences in ADG among the dietary treatments, but adding either choice white grease or soybean oil resulted in a linear reduction in ADFI. This result was expected because it is well documented that an increase in energy density from adding supplemental fat or oil reduces feed intake in pigs. As a result, there was a linear increase in gain efficiency (G:F) when diets contained increasing proportions of calories from choice white grease or soybean oil. These results are consistent with those reported in a previous study (Morgan et al., 1992), but different than those reported by Apple et al. (2009), who showed no differences in ADG, ADFI, or G:F when pigs were fed diets containing 5% beef tallow, poultry fat, or soybean oil. Benz et al. (2011) reported that feeding diets containing 5% soybean oil improved ADG, but no improvement was observed when diets contained 5% choice white grease. Penner et al. (2018) showed that average daily ME intake was similar among all treatments except the pigs

fed 40% of dietary calories from choice white grease. These results suggest that regardless of lipid source, feeding diets containing increasing proportions of calories from choice white grease or soybean oil linearly increased lean gain efficiency.

Table 15. *Growth performance of pigs fed diets containing either choice white grease or soybean oil added at 0, 10, 20, 30 or 40% of total caloric intake (adapted from Penner et al., 2018)*

Measure	Control	Choice White Grease				Soybean Oil			
		10%	20%	30%	40%	10%	20%	30%	40%
ADG, kg/day	0.88	0.85	1.03	0.98	0.89	0.92	0.96	0.92	0.93
ADFI, kg/day	3.14^{a}	2.83^{bcde}	2.96^{abc}	2.58^{cde}	2.17^{f}	3.01^{ab}	2.71^{bcde}	2.48^{def}	2.35^{ef}
G:F	0.276^{c}	0.295^{c}	0.347^{b}	0.381^{ab}	0.403^{a}	0.307^{c}	0.354^{b}	0.370^{ab}	0.394^{a}
Avg, daily ME intake, Mcal	11.9^{ab}	11.3^{abc}	12.4^{a}	11.5^{abc}	10.2^{c}	11.9^{b}	11.3^{bc}	10.9^{bc}	10.4^{bc}
Lean gain efficiency, g/kg	97^{e}	105^{de}	113^{cde}	131^{ab}	116^{a}	110^{de}	120^{bcd}	127^{abc}	128^{ab}

^{a,b,c,d,e,f}Means within rows with uncommon superscripts are different (P < 0.05).

Although some differences in carcass characteristics and composition were observed among individual dietary treatments, there were no major overall trends in responses from feeding either choice white grease or soybean oil, except that pigs fed choice white grease tended to have greater backfat thickness than pigs fed soybean oil **(Table 16).** Although there were no significant differences among treatments, carcass lean gain per day appeared to improve by the addition of increasing amounts of calories from choice white grease or soybean oil in the diets. Furthermore, pigs fed the lipid supplemented diets appeared to have more carcass fat and skin, and less lean than pigs fed the control diet. These results are similar to those reported by (Benz et al., 2011), where they observed no differences in backfat, loin depth, and carcass lean percentage when pigs were fed diets containing either choice white grease or soybean oil compared to feeding control diets.

Table 16. *Carcass characteristics and composition of pigs fed diets containing either choice white grease or soybean oil added at 0, 10, 20, 30 or 40% of total caloric intake (adapted from Penner et al., 2018)*

Measure	Control	Choice White Grease				Soybean Oil			
		10%	20%	30%	40%	10%	20%	30%	40%
Characteristic									
Carcass weight,kg	80.7^{a}	81.2^{ab}	83.9^{bc}	85.2^{c}	83.6^{bc}	83.4^{bc}	83.4^{abc}	82.1^{ab}	82.3^{ab}
Dressing, %	74.2^{ab}	74.3^{ab}	74.9^{ab}	75.1^{a}	74.3^{ab}	74.8^{ab}	74.3^{ab}	73.6^{a}	74.1^{ab}
Carcass length, cm	80.8	81.1	81.5	81.3	81.1	81.9	81.8	82.6	80.7
10^{th} rib backfat, cm	2.50	2.41	2.94	2.99	2.93	2.54	2.58	2.56	2.94
Loin muscle area, cm^2	38.2	35.6	37.6	38.0	38.3	39.7	38.1	35.8	35.0
Carcass lean gain, g/day	298	298	333	338	313	328	321	315	306
Lean color score	2.83^{ab}	2.83^{ab}	3.00^{a}	2.83^{ab}	2.35^{b}	2.67^{ab}	2.83^{ab}	3.00^{a}	2.67^{ab}
Marbling score	2.67^{ab}	2.67^{ab}	2.83^{a}	2.50^{ab}	2.33^{ab}	2.67^{ab}	2.00^{b}	2.83^{d}	2.33^{ab}
Lean firmness score	2.83^{d}	2.50^{de}	2.83^{d}	2.67^{de}	2.35^{de}	2.50^{de}	2.33^{de}	2.83^{d}	2.17^{e}
Composition									
Lean, %	50.2	47.3	48.0	46.0	48.5	48.2	48.1	48.4	46.9
Fat, %	30.7^{a}	32.9^{ab}	33.5^{ab}	36.6^{b}	33.1^{ab}	33.7^{ab}	33.8^{ab}	31.6^{ab}	34.7^{ab}
Bone, %	13.8^{ab}	14.9^{a}	13.9^{ab}	12.4^{a}	13.3^{ab}	13.0^{b}	13.7^{ab}	14.7^{a}	13.5^{ab}
Skin, %	5.33^{a}	4.89^{ab}	4.67^{ab}	4.91^{ab}	5.18^{ab}	5.10^{ab}	4.50^{b}	5.27^{a}	4.87^{ab}

^{a,b,c}Means within rows with uncommon superscripts are different (P < 0.05).
^{d,e}Means within rows with uncommon superscripts are different (P < 0.10).

Changes in fatty acid composition of backfat were more pronounced in pigs fed the soybean oil diets compared with those fed the choice white grease diets. Feeding diets containing choice white grease to growing-finishing pigs resulted in decreased saturated fatty acid (SFA), increased monounsaturated fatty acids (MUFA), with no change in polyunsaturated fatty acid (PUFA) content in backfat (data not shown). In contrast, feeding diets containing increasing calories from soybean oil linearly affected all fatty acid concentra-

tions in each of the three layers of carcass backfat (data not shown). When feeding the diet containing 40% of the calories from soybean oil, SFA content of backfat decreased by almost 50%, MUFA content decreased by about 33%, and PUFA content increased by more than two-fold, resulting in almost a 5-fold increase in the PUFA to SFA ratio. These results were expected because soybean oil contains a high concentration of linoleic acid, of which a large proportion is directly deposited in adipose tissue. Apple et al. (2009) reported similar increases in PUFA content of backfat when feeding diets containing 5% soybean oil.

The intermuscular fat depot in ham had similar changes to dietary lipids as observed for the backfat fatty acid profile **(Table 17).** The addition of increasing amounts of choice white grease to growing-finishing pig diets had minimal effects on the proportions of individual fatty acids, as well as SFA, MUFA, lipid content, and unsaturated:saturated fatty acids in loin (Longissimus dorsi) muscle (Table 17). In contrast, the addition of increasing calories from soybean oil to the diets linearly decreased SFA and MUFA content, and linearly increased PUFA content by greater than 140%. Furthermore, concentrations of SFA and MUFA were slightly greater, and concentrations of PUFA were slightly less in Longissimus muscle than in triceps brachii or biceps femoris muscles (data not shown). These results indicate that dietary inclusion of soybean oil in growing-finishing pig diets for 10 weeks before slaughter is effective in decreasing SFA and MUFA content, and increasing PUFA content of pork muscle without adversely affecting growth performance or other carcass characteristics. When humans consumed pork and lard from pigs fed the control compared with these food products from pigs fed the diets containing 40% of calories from soybean oil diets in a previous study, total plasma cholesterol and LDL-cholesterol were reduced and fatty acid composition was shifted toward more PUFAs in plasma and erythrocytes (Stewart et al., 2001). As a result, eating pork from pigs fed soybean oil diets may be effective in reducing the risk of atherosclerosis and heart disease in humans. These benefits were not observed when feeding growing-finishing pig diets containing choice white grease.

Table 17. *Fatty acid composition (percentage of total fatty acids) of intermuscular fat from ham, and loin (Longissimus dorsi) muscle of pigs fed diets containing either choice white grease or soybean oil added at 0, 10, 20, 30 or 40% of total caloric intake (adapted from Penner et al., 2018)*

Measure	Control	Choice White Grease				Soybean Oil			
		10%	20%	30%	40%	10%	20%	30%	40%
Ham									
C16:0, %	26.7^{a}	25.7^{a}	26.6^{a}	25.1^{a}	24.5^{ab}	25.8^{a}	21.9^{b}	18.2^{c}	16.4^{c}
C18:0, %	11.4^{a}	10.6^{ab}	10.0^{ab}	9.3b^{c}	10.1^{ab}	10.2^{ab}	9.6^{b}	7.7^{cd}	7.2^{d}
C18:1, %	41.7^{a}	43.8^{a}	41.3^{a}	43.6^{a}	44.8^{a}	35.7^{b}	31.1^{bc}	30.4^{c}	29.9^{c}
C18:2, %	13.8^{f}	14.1^{f}	15.1^{f}	15.3^{f}	14.6^{f}	21.9^{g}	30.9^{h}	37.7^{i}	39.4^{i}
C18:3, %	0.29^{a}	0.29^{a}	0.39^{a}	0.43^{a}	0.39^{a}	1.07^{b}	2.07^{c}	2.93^{d}	3.39^{e}
Total SFA, %	39.9^{a}	38.0^{a}	38.6^{a}	36.3^{ab}	36.3^{ab}	37.9^{a}	32.9^{b}	27.1^{c}	24.6^{c}
Total MUFA, %	45.6^{a}	47.4^{a}	45.6^{a}	47.6^{a}	48.4^{a}	38.8^{b}	33.7^{c}	32.2^{c}	31.9^{c}
Total PUFA, %	14.5^{f}	14.6^{f}	15.8^{f}	16.1^{f}	15.2^{f}	23.4^{g}	33.5^{h}	40.7^{i}	43.5^{i}
U:S	1.52^{a}	1.65^{a}	1.61^{a}	1.77^{ab}	1.78^{ab}	1.68^{a}	2.12^{b}	2.76^{c}	3.15^{c}
Loin									
C16:0, %	27.5^{a}	26.9^{a}	26.4^{a}	26.0^{ab}	26.1^{ab}	26.8^{a}	24.5^{b}	22.3^{c}	19.3^{d}
C18:0, %	12.3^{a}	12.0^{ab}	11.2^{ab}	11.0^{bc}	11.2^{ab}	11.7^{ab}	11.5^{ab}	10.1^{c}	8.7^{d}
C18:1, %	43.2^{ab}	46.0^{a}	45.2^{a}	44.4^{ab}	40.8^{bc}	39.1^{c}	38.5^{c}	32.5^{d}	31.6^{e}
C18:2, %	7.4^{a}	6.8^{a}	8.1^{a}	9.9^{ab}	12.8^{b}	12.6^{b}	16.6^{c}	25.8^{d}	31.4^{e}
C18:3, %	0.19^{f}	0.19^{f}	0.33^{f}	0.25^{f}	0.54^{fg}	0.60^{fg}	1.03^{g}	2.41^{h}	3.16^{i}
Total SFA, %	41.4^{a}	40.4^{ab}	39.2^{abc}	38.6^{bc}	39.0^{abc}	40.2^{abc}	37.4^{c}	33.8^{d}	29.3^{e}
Total MUFA, %	49.8^{ab}	51.7^{a}	51.0^{a}	50.2^{a}	46.4^{b}	45.0^{c}	43.5^{c}	36.1^{d}	34.6^{d}
Total PUFA, %	8.8^{a}	8.0^{a}	9.8^{a}	11.2^{ab}	14.6^{b}	14.8^{b}	19.1^{c}	30.0^{d}	36.1^{e}
Total lipids, %	3.24^{ab}	3.82^{a}	3.25^{ab}	3.47^{a}	3.18^{ab}	2.47^{b}	2.60^{b}	3.07^{ab}	3.46^{a}
U:S	1.42^{a}	1.48^{ab}	1.57^{ab}	1.60^{ab}	1.58^{ab}	1.50^{ab}	1.68^{b}	1.97^{c}	2.44^{d}

^{a,b,c,d,e}**Means within rows with uncommon superscripts are different (P < 0.05).**
^{f,g,h,i}**Means within rows with uncommon superscripts are different (P < 0.05).**

Table 18. *Average growth rate and feed:gain responses of moderately heat-stressed pigs fed increasing dietary levels of soybean oil (SO) among high and reduced crude protein diets compared with pigs housed under thermoneutral conditions (adapted from Wolp et al., 2012)*

Measure	Control	1.5% SO	3.0% SO	4.5% SO
ADG, g	1,017	911[b]	940[ab]	985[a]
F:G	2.29	2.62[a]	2.50[ab]	2.42[a]

BENEFITS OF SOYBEAN OIL IN GROWING-FINISHING PIG DIETS UNDER HEAT STRESS CONDITIONS

When pigs are exposed to excessive heat in commercial production conditions, their rate and efficiency of growth is compromised due to several factors including reduced feed intake (Witte et al., 2000; Kiefer et al., 2005). These adverse effects of heat stress on growth performance can be minimized by reducing dietary crude protein levels, with adequate supplementation of crystalline amino acids to meet daily digestible amino acid requirements, which has been shown to reduce body heat production (Stahly and Cromwell, 1986). The addition of supplemental lipid to swine diets can have a greater effect on reducing heat increment compared with decreasing dietary crude protein content (Li and Sauer, 1994; Noblet et al., 2001; Spencer et al., 2005). Therefore, Wolp et al. (2012) evaluated the effects of feeding isocaloric diets containing increasing levels of soybean oil (1.5, 3.0, and 4.5%), and reduced crude protein content (15.5% vs. 18%) with supplementation of adequate amounts of crystalline amino acids, on growth performance of pigs housed under heat stress conditions (32°C, 60 to 70% relative humidity) compared with a thermoneutral environment (22°C, 60 to 70% relative humidity). Results from this study showed that the high environmental temperature conditions reduced growth rate and feed conversion compared with pigs housed under thermoneutral conditions **(Table 18).** However, the addition of 4.5% soybean oil improved ADG and reduced F:G of pigs housed in heat stress conditions, compared with feeding diets containing 1.5% soybean oil, regardless of whether the dietary crude protein level was reduced. Therefore, the addition of 4.5% soybean oil to diets fed to growing-finishing pigs can be effective in partially restoring growth performance of pigs under moderate heat stress conditions.

SUPPLEMENTAL SOYBEAN OIL IN GESTATING AND LACTATING SOW DIETS

It is well-documented that adding supplemental fat or oil to sow lactation diets increases the energy density of the diets and increases energy intake even though feed intake may be decreased (Schoenherr et al., 1989; Renaudeau et al., 2001). Furthermore, feeding lipid supplemented diets to lactating sows results in increased milk fat content (Schoenherr et al., 1989; van den Brand et al., 2000; Renaudeau et al., 2001), but generally does not affect body weight loss, backfat loss, or reproductive performance of sows. However, when feeding lipid supplemented diets to sows before farrowing, the increase in lipid content of

colostrum may reduce pre-weaning mortality, especially in sow herds where piglet pre-weaning mortality is high (Pettigrew, 1981).

Quiniou et al. (2008) cited a French study by Mourot (2001) that provided some evidence that the addition of supplemental lipids to gestation and lactation diets increases the number of adipose cells in adipose tissue and Longissimus dorsi muscle of piglets at birth, which can lead to greater lipid accretion in these body tissues. Although very few studies have evaluated the subsequent effects of feeding lipid supplemented diets to sows on growth and carcass composition of their litters, this response may be beneficial for improving pork quality because modern genetic lines have reduced lipid deposition in adipose tissue and muscle (Tribout and Bidanel, 1999; Labroue et al., 2001). Therefore, Quiniou et al. (2008) conducted a study to compared the performance effects of feeding isocaloric diets containing 11% corn starch or 5% soybean oil (formulated on a NE basis) during gestation (day 35 to farrowing) and lactation (28 days), or lactation only. Sow and litter performance through weaning, and subsequent growth performance and carcass characteristics of the progeny litters from weaning to market weight were evaluated.

As shown in **Table 19,** feeding the 5% soybean oil diets during gestation and lactation had no effect on the number of total pigs born, born alive, and weaned, but increased pig and litter weights at weaning (Quiniou et al., 2008). Furthermore, sows fed the soybean oil diets had reduced number of stillborns, mortality of pigs born alive within the first 24 hours after birth, and overall pre-weaning mortality compared to sows fed equivalent energy from the corn starch diets. Similar effects were also observed when sows were fed the 5% soybean oil diet during lactation only, where there was an improvement in litter weight gain, even though litters consumed less creep feed than those from sows fed the corn starch diet **(Table 19).** Due to a relatively low number of sows per treatment, there were no significant differences in sow body weight loss and backfat loss during lactation between dietary treatments. However, when sows were fed the soybean oil diet during lactation only, they had a shorter wean-to-estrus interval **(Table 20).** Furthermore, there were no differences in growth performance of progeny from these sows during the nursery and growing-finishing periods, nor differences in carcass characteristics at slaughter. However, pigs from sows fed 5% soybean oil diets during gestation and lactation had greater carcass lipid content at weaning, which was due to an increase in the number of adipose cells in dorsal subcutaneous adipose tissue and Longissimus dorsi muscle (data not shown). This advantage from feeding soybean oil diets to dams carried through the growing-finishing period to slaughter, where the lipid content of Longissimus dorsi muscle had greater lipid content than progeny from sows fed the corn starch diets **(Table 21).** These results suggest that adding 5% soybean oil to gestating and lactating sow diets may be beneficial for improving lipid content and pork quality of offspring.

Table 19. *Effects of feeding isocaloric corn starch and soybean oil diets to sows during gestation and lactation, or lactation only, on litter performance and mortality (adapted from Quiniou et al., 2008).*

Measure	Gestation and Lactation		Lactation	
	Corn starch	Soybean oil	Corn starch	Soybean oil
No. sows	32	35	70	73
No. piglets/litter				
Total born	14.5	14.0	14.5	13.7
Born alive	13.5	13.4	13.5[a]	12.7[b]
Weaned	11.2	11.3	11.4	11.3
Body weight, kg/piglet				
Birth (total born)	1.51	1.51	1.54	1.53
Weaning	9.09[b]	9.49[a]	8.85	8.95
Body weight, kg/litter				
Birth (total born)	21.2	21.1	21.7	20.7
Weaning	101.0[b]	107.8[a]	100.2	101.2

Continuation Table 19. *Effects of feeding isocaloric corn starch and soybean oil diets to sows during gestation and lactation, or lactation only, on litter performance and mortality (adapted from Quiniou et al., 2008).*

Measure	Gestation and Lactation		Lactation	
	Corn starch	Soybean oil	Corn starch	Soybean oil
Daily litter weight gain, kg/litter	3.01[b]	3.20[a]	2.83[b]	2.92[a]
Creep feed intake, kg/litter	3.7	3.6	4.2[a]	3.4[b]
Mortality, %				
Stillborn	7.5[b]	4.0[a]		
Within first 24 hrs post-farrowing	6.3	6.9		
After 24 hours post-farrowing	12.6[y]	8.7[x]	10.7[b]	8.1[a]
Total pre-weaning	24.3[b]	18.6[a]		

[a,b]Means with uncommon superscripts within feeding period are different (P < 0.05).
[x,y]Means with uncommon superscripts within feeding period are different (P < 0.06).

Table 20. *Effects of feeding isocaloric corn starch and soybean oil diets to sows during gestation and lactation, or lactation only, on sow body characteristics and reproductive performance after weaning (adapted from Quiniou et al., 2008).*

Measure	Gestation and Lactation		Lactation	
	Corn starch	Soybean oil	Corn starch	Soybean oil
Average parity	3.5	3.5	3.0	3.4
Body weight, kg				
Day 7 of gestation	202	201	198	201
After farrowing	253	252	254	257
Weaning	231[x]	225[y]	227	234
Backfat thickness (P2), mm				
Day 7 of gestation	16.6	16.8	15.7	15.6
Day 108 of gestation	19.8	20.3	19.4	19.4
Weaning	16.2	15.6	15.7	15.4
ADFI, kg/sow	6.53	6.36	6.27	6.09
NE intake, Mcal/day/sow	14.83	15.31	14.24	14.55
% of sows anestrus	9.4	8.6	5.7	4.1
Weaning to estrus interval, days	4.0	4.0	5.1[b]	4.7[a]

[a,b]Means with uncommon superscripts within feeding period are different (P < 0.05).
[x,y]Means with uncommon superscripts within feeding period are different (P < 0.08).

Table 21. *Effects of feeding isocaloric corn starch and soybean oil diets to sows during gestation and lactation, or lactation only, on growth performance and carcass characteristics of progeny from weaning to slaughter (adapted from Quiniou et al., 2008).*

Measure	Gestation and Lactation		Lactation	
	Corn starch	Soybean oil	Corn starch	Soybean oil
Nursery				
Body weight, kg				
Weaning (28 days of age)	9.26	9.69	8.00	8.49
61 days of age	26.1	26.7	24.8	25.7
ADG, g	509	516	509	523
ADFI, g	710	713	737	758
F:G	1.40	1.39	1.45	1.45
Growing-finishing				
Initial body weight, kg	26.4	27.0	25.0	26.1
Final body weight, kg	112.6	112.4	109.2	110.2
Feeding period, days	100.4	97.7	93.8	93.1
ADG, g	861	877	897	904
F:G	2.63	2.67	2.52	2.52
Hot carcass weight, kg	89.5	88.9	86.9	86.5
Carcass lean,%	61.3	61.2	61.7	61.2
Total lipid in dorsal subcutaneous adipose tissue, %	70.37	71.77	-	-
Total lipid in Longissimus dorsi, %	2.58[b]	3.46[a]	-	-

[a,b]Means with uncommon superscripts within feeding period are different (P < 0.05).

U.S. DEGUMMED SOYBEAN OIL IS AN EXCELLENT SOURCE OF ESSENTIAL FATTY ACIDS FOR SOWS

Sow productivity has increased dramatically over the last several decades, with the most productive maternal genetic lines capable of producing more than 15 total pigs born/litter and more than 9.2 kg of milk produced per day (Stalder, 2003). Highly prolific sows often have less body fat reserves and less feed intake (Hermesch et al., 2000), while energy and nutrient demands for greater milk production are increased. Therefore, the need for supplemental lipids in sow lactation diets, especially under heat stress conditions (Pettigrew, 1981), is likely greater than ever.

Ensuring adequate intake of essential fatty acids (linoleic and linolenic acid) during gestation and lactation is essential to achieve and maintain pregnancy and increase subsequent litter size (Rosero et al., 2016a). Soybean oil is unique compared with other lipid sources because it contains high concentrations of both linoleic and linolenic acid. These fatty acids are considered to be essential and must be present in adequate amounts in the diet because animal do not have desaturase enzymes capable of adding double bonds beyond carbon 10 of octadecenoic fatty acids. However, octadecenoic acids (linoleic and α-linolenic) can be converted to long-chain polyunsaturated fatty acids by microsomal desaturase and elongase enzymes (Sprecher, 2000; Jacobi et al., 2001). Therefore, linoleic acid can be converted to ϒ-linoleic (C18:3n-6), dihomo-ϒ-linolenic (C20:3n-6), and arachidonic (C20:4n-6), and other fatty acids. Alpha-linolenic acid (C18:3n-3) can be converted to eicosatetraenoic (C20:4n-3), eicosapentaenoic (C20:5n-3), docosahexaenoic (C22:6n-3) acids, and other important long-chain fatty acids (Palmquist, 2009). These essential fatty acids are important for a number of metabolic processes including reproduction (Palmquist, 2009). However, current recommendations for essential daily linoleic acid intake of sows is 6 g/day (0.1% of the diet), with no recommended requirement for α-linolenic acid (NRC, 2012). Therefore, the requirements for these essential fatty acids in sow diets need to be re-evaluated.

Rosero (2016b) summarized data from 6 published studies and estimated that sows fed diets without supplemental linoleic acid during lactation had a negative balance of -25.49 g/day, and a negative balance of -2.75 g/day of α-linolenic acid, which resulted in decreased farrowing rate (< 75%) and increased culling rate (> 25% in weaned sows). These effects were more dramatic as sow age (parity) increased because of a progressive reduction in essential fatty acid status during successive reproductive cycles.

Providing adequate linoleic acid intake during lactation increased the proportion of sows that farrowed and increased the number of total pigs born in the subsequent reproductive cycle. Increasing α-linolenic acid intake resulted in more rapid return to estrus after weaning (wean-to estrus interval – 4 days), sows mated:sows weaned (94%), and greater retention of pregnancy (sows pregnant:sows mated = 98%). Based on these results, Rosero et al. (2016b) concluded that the minimum dietary intake of 125 g/day and 10 g/day of linoleic acid and linolenic acid, respectively, is required during lactation to achieve optimal reproductive performance. Soybean oil can serve as an excellent source of both linoleic and linolenic acid to achieve these essential fatty acid consumption levels for optimal sow reproductive performance.

SUMMARY

High quality U.S. soybean oil has been shown to contain higher DE, ME, and NE content compared with other commonly used fats and oils in swine diets. Although, energy estimates for soybean oil vary among various published sources, there is evidence that the NRC (2012) estimates are reasonably accurate. Several DE, ME, and NE prediction equations have been developed, but they either result in inaccurate estimates or need further validation for use. Although feeding adequately heat-processed (extruded or roasted) full-fat soybeans can provide supplemental energy to swine diets, the digestibility of oil in full-fat soybeans is substantially less than in extracted soybean oil, which needs to be considered before adopting this method of lipid supplementation. The addition of U.S. soybean oil to swine diets has been shown to increase amino acid digestibility, as well as digestibility of some minerals, especially calcium and phosphorus, compared with other lipid sources. U.S. soybean oil is an excellent supplemental energy source in weaned pig and growing-finishing diets to support optimal growth performance, caloric and nutritional efficiency, and carcass characteristics. Although soybean oil, like other vegetable oils, contain high concentrations of polyunsaturated fatty acids which reduce pork fat firmness in pork carcasses, the concentrations of PUFA in pork meat are increased when feeding diets containing soybean oil to growing-finishing as well as progeny from sows fed soybean oil diets. These improvements in PUFA content in pork meat may provide beneficial health effects for humans and reduce the risk of cardiovascular disease. Feeding diets containing supplemental U.S. soybean oil have also been shown to be beneficial in partially alleviating the adverse effects on growth performance under heat stress conditions. Lastly, there are numerous benefits of adding U.S. soybean oil to sow diets which include improved sow and litter performance, and increased supplementation of linoleic and linolenic acid from soybean oil can improve reproductive performance of high producing mature sows.

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Chapter

09

Feeding Applications of U.S. Soybean Oil in Broiler Diets

INTRODUCTION

The addition of U.S. soybean oil to broiler diets provides several benefits including increasing the caloric density to meet the energy requirements of fast growing birds, reduces dust in broiler production facilities, improves diet palatability, reduces particle separation in mash diets, provides essential fatty acids, serves as a carrier of lipid soluble vitamins, and reduces the rate of passage of digesta (Mateos and Sell, 1981b), which enhances digestion and absorption of nutrients.

Many factors affect the energy value and utilization of lipids in poultry. Bird related factors include age, gender, breed, species, and intestinal infections (Ravindran et al., 2016). Diet related factors include degree of fatty acid unsaturation in lipids, dietary inclusion levels of lipids, position of fatty acids in triglycerides, extent of lipid oxidation, type of cereal grains in basal diets, feed processing, dietary calcium levels, and the potential presence of anti-nutritional factors (Ravindran et al., 2016).

METABOLIZABLE ENERGY CONTENT OF SOYBEAN OIL

Determination of the true energy contribution of lipids to poultry diets is challenging (Ravindran et al., 2016). In general, two methods of expressing metabolizable energy (ME) content of poultry feeds and ingredients have been used: true metabolizable energy (TME) and apparent metabolizable energy (AME). True metabolizable energy involves force feeding a test ingredient without the use of a basal diet and collecting excreta within a 48-hour collection period to determine TME by difference (intake – excretion). However, the TME method has several drawbacks and is seldom used in practical diet formulations because of its inherent inaccuracies. In contrast, AME is determined by the difference between the gross energy (GE) of feed consumed and the GE in excreta, and is determined by providing ad libitum access to basal diets containing a lipid source over several days. Apparent metabolizable energy is the most common method used by poultry nutritionists when formulating practical diets. Adjustments in AME content are commonly made based on correction for nitrogen retained in the body, and is designated as (AMEn). However, experimental methodologies to determine AMEn also differ among reported studies, and as a result, provide variable estimates of ME content of various lipid sources. Mateos and Sell (1981a) and Irandoust et al. (2012) have evaluated the benefits and limitations of using these methodologies. Therefore, one of the greatest challenges of optimizing the economic and nutritional value of feed fats and oils is to determine the appropriate AMEn value for the lipid source being used in the feed formulation.

Soybean oil is widely considered to have the greatest AME content for broilers among all common fats and oils **(Table 1).** This is due to several factors including its high polyunsaturated fatty acid (PUFA) content, low moisture, insolubles, and unsaponifiables (MIU) content, as well as its low free fatty acid (FFA) content and peroxidation. However, as for all lipids, estimates of AME content from published studies vary. Variability in these estimates are due to several factors including age of bird, unsaturated:saturated (U:S) fatty acid and FFA content, fatty acid chain length, fatty acid position on glycerol of triglycerides, and MIU content (Wiseman et al., 1991).

Tancharoenrat et al. (2013) reported that the AME content of soybean oil was 4,490 kcal/kg for broilers at one week of age, but increased to 8,168 kcal/kg at 2 weeks of age, 9,172 kcal/kg at 3 weeks of age, and was 8,861 kcal/kg at 5 weeks of age. Similar effects of age on AME content have been observed for other fats and oils, where digestibility and subsequent AME content increases with bird age **(Table 2).** This response occurs because newly hatched chicks have a poorly developed ability to secrete lipase and fatty acid binding protein synthesis (Krogdahl, 1985), as well as limited bile secretion

and inefficient bile recirculation (Smallwood et al., 1972; Serafin and Nesheim, 1967). However, these important lipid digestion capabilities increase as the bird increases in age, and the activity of all digestive enzymes have also been reported to increase with bird age (Nitsan et al., 1991). These findings suggest that different AME values should be assigned to fats and oils, including soybean oil, when formulating diets for different stages of growth to achieve optimal caloric efficiency in precision broiler feeding programs. Unfortunately, this is rarely done in practice because of uncertainty and variability of AME values of the actual soybean oil source being used.

The AME content of lipids increases as the ratio of unsaturated to saturated fatty acids increases. Soybean oil contains one of the highest concentrations of polyunsaturated fatty acids (PUFA) of all commonly used lipid sources in poultry diets, which is the main reason for its high AME content for broilers. Another reason the high AME content in U.S. soybean oil is that it contains low concentrations of FFA. Studies have shown that as FFA content increases in a lipid source, AME content generally declines (Wiseman et al., 1991). However, this response has been shown to not occur in corn oil, which has a similar fatty acid profile to soybean oil (Kerr et al., 2016).

A summary of published AME values for soybean oil are shown in **Table 3,** with AME content ranging from 8,123 kcal/kg (Murugesan et al., 2017) to 11,106 kcal/kg (Pesti et aal., 2002), and an average AME content of 9,220 kcal/kg. Conservatively, the AME values reported by Viera et al. (2015) for young birds (8,348 kcal/kg) and older birds (9,283 kcal/kg) seem appropriate for avoiding overestimation of AME content of soybean oil in broiler diets, which are commonly added at low diet inclusion rates (2 to 4%).

Table 1. *Comparison of average apparent metabolizable energy (AME) values of common lipid sources used in broiler diets (adapted from Ravindran et al., 2016)*

Lipid source	AME, kcal/kg
Soybean oil	9,816
Yellow grease	9,530
Animal-vegetable blends	9,399
Poultry fat	9,005
Lard	8,151
Acidulated soybean soapstock	8,113
Tallow	7,416
Palm oil	6,999

Table 2. *Comparison of digestibility of common lipid sources used in broiler diets at different ages (adapted from Dei, 2011)*

Lipid source	3 to 4 weeks of age	>4 weeks of age
Soybean oil	96	96
Corn oil	84	95
Lard	92	93
Tallow	70	76
Fish oil	88	97
Palm oil	74	-

Table 3. *Summary of apparent metabolizable energy (AME) estimates of soybean oil in broiler diets*

Dietary inclusion rate	Age of bird	Kcal/kg	Reference
2 to 6%	19 days	9,673 to 10,199	Wiseman et al. (1986)
9%	24 days	8,527	Huyghebaert et al. (1988)
10 to 20%	-	8,020 to 8,795	NRC (1994)
4%	Adult rooster	10,533	Blanch et al. (1996)
-	-	9,004	Sauvant et al. (2002)
6%	10 days	11,106	Pesti et al. (2002)
6%	40 days	9,554	Pesti et al. (2002)
3.5%	Adult rooster	9,124	Irandoust et al. (2012)
2, 4, and 8%	7 days	8,348	Vieira et al. (2015)
2, 4, and 8%	35 days	9,283	Vieira et al. (2015)
-	-	8,790	Rostagno (2017)
3, 6, and 9%	21 days	8,123	Murugesan et al. (2017)

ENERGY PREDICTION EQUATIONS

There is considerable interest in developing and using equations to accurately estimate AME content of lipids based on chemical composition. Although several equations have been developed, their accuracy in predicting in vivo determined AME content is generally poor because they are too simplistic and do not include a number of important predictive variables to allow them to be useful in commercial applications. For example, lipids that contain increased concentrations of MIU and oxidation products are generally expected to result in decreased AME content, but studies have shown that using only these measures results in poor AME prediction (Huyghebaert et al., 1988; Pesti et al., 2002). However, combining these measures of lipid quality with lipid fatty acid profiles may provide better estimates (Huyghebaert et al., 1988). Furthermore, simple equations based on the unsaturated:saturated (U:S) fatty acid content (Ketels and De Groote, 1989), or more complex regression equations using FFA content and concentrations of major fatty acid concentrations (Huyghebaert et al., 1988) have been reported.

Perhaps the most widely used equations to predict AME content of lipids for broilers is the equation developed by Wiseman et al. (1991), which includes age of bird, U:S, and FFA content of lipids. However, a recent study comparing actual and predicted AME content of distillers corn oil (Kerr et al., 2016) using the Wiseman et al. (1998) equations resulted in substantial overestimation of AME for broilers compared to in vivo AME values. Results from this study are an excellent reminder that the potential use of published AME prediction equations should be based on the lipid sources from which they were derived because of the widely differing fatty acid profiles and oxidation indicators among various feed fats and oil in the market. Research is underway to develop more accurate AME prediction equations using a combination of fatty acid profiles, quality, and oxidation indicator measurements to provide more accurate estimates. In fact, results from recent studies (Lindblom et al., 2019) suggest that p-anisidine value, 2,4-decadienal, total polar compounds, and polymerized triacylglycerides should be measured and used as indicators of lipid oxidation status for soybean oil because they were consistently correlated with growth performance responses. Therefore, use of existing equations to estimate AME content of soybean oil is not recommended because it appears that more comprehensive and complex regression equations are needed to accurately predict AME and growth performance responses to soybean oil based on oxidation status.

"EXTRA CALORIC EFFECT" OF SOYBEAN OIL IN BROILER DIETS

The addition of lipids to broiler diets has often been described as having an "extra caloric effect" because it often results in greater improvement in growth rate and feed conversion above that predicted from its energy value. Nitsan et al. (1997) suggested that the true nutritional value of lipids may be better assessed by determining the net energy deposition in the body rather than by AME content. This suggestion was based on research showing that the AME content of lipids declines with increasing dietary inclusion rates (Jensen et al., 1970; Sell et al., 1976; Wiseman and Salvador, 1989), and that dietary soybean oil supplementation decreases body fat in broilers selected for high or low abdominal adipose tissue (Keren-Zvi et al., 1990). Therefore, Nitsan et al. (1997) conducted a study to evaluate the extra caloric effect of soybean oil added to mash or pelleted diets at two dietary energy densities to determine ME and net energy (NE) deposition in broilers. Diets consisted of 2,892 kcal ME/kg with no added soybean oil (L0), 2,892 kcal ME/kg with 3% added soybean oil (L3), 3,107 kcal/kg ME with 3.4% soybean oil (H3), or 3,107 kcal ME/kg with 6% added soybean oil (H6), using an AME value for soybean oil of 9,465 kcal/kg.

The greatest effect of soybean oil supplementation on body weight was during 3 to 6 weeks of age **(Table 4).** Body weight gain was significantly improved by 6.9% by adding soybean oil to the low energy diet, and was numerically increased by 3.4% for broilers fed the high energy diets. Feed intake was not affected by dietary

energy level or soybean oil supplementation, and gain:feed (G:F) was greater when feeding the high energy diet compared with the low energy diet. These results indicate that the extra-caloric effect of soybean oil for improving growth rate was more pronounced during the period of rapid growth (3 to 6 weeks of age) when lipid digestibility is near its maximum. Apparent retention of dry matter and nitrogen was not affected by dietary energy level or soybean oil concentration in diets, but starch digestibility was reduced by adding soybean oil in both low and high energy diets (data not shown). Lipid digestibility increased by adding soybean oil to the diet, and was greater in the high energy diets compared with the low energy diets (data not shown). Therefore, the decrease in starch digestibility was overcome by the increase in lipid digestibility resulting in greater measured AMEn content of the high energy diets (H3 = 3,307 kcal/kg; H6 = 3,203 kcal/kg) containing soybean oil was greater than the low energy diet without soybean oil supplementation (2,964 kcal/kg).

Although the addition of soybean oil to the diet had no effect on body composition **(Table 5),** NE deposition was greater when soybean oil was added to the low and high energy diets compared with the low energy diet without supplemental soybean oil (L0). When relatively low amounts of oil (i.e. 3%) is added to diets, it is assumed that a substantial portion of the fatty acids are directly transferred to be deposited in body tissues. This is a more energetically efficient process than synthesizing tissue lipids from carbohydrates, resulting in a reduction in heat production and improvement in NE retention (Nitsan et al., 1997). However, when excess highly unsaturated oil (e.g. soybean oil) is added to the diet, a greater proportion of fatty acids are likely used as energy sources and released as heat, which may explain why an "extra-caloric effect" of soybean oil was observed when added at 3% of the diet, but not at 6% of the diet (Nitsan et al., 1997). These results show that the "extra caloric effect" of adding soybean oil to broiler diets is greater for low energy diets containing supplemental oil based on body weight gain and G:F responses. When expressed on the basis of net energy retention, this "extra-caloric effect" is greater in diets containing 3% soybean oil than diets with 6% soybean oil.

Table 4. *Effects of supplemental soybean oil (0, 3, or 6%) in low (L) and high (H) energy diets on body weight gain, feed intake, and gain:feed from 3 to 7 weeks of age (adapted from Nitsan et al., 1997)*

Age, weeks	L0	L3	H3	H6
Body weight gain, g				
Week 3 to 4	350^{b}	356^{b}	388^{a}	393^{a}
Week 4 to 5	293^{b}	318^{b}	321^{ab}	332^{a}
Week 5 to 6	312^{a}	347^{a}	331^{a}	350^{a}
Weeks 3 to 6	955^{c}	1,021^{b}	1,040^{ab}	1,075^{a}
Week 6 to 7	441^{a}	440^{a}	431^{a}	432^{a}
Weeks 3 to 7	1,396^{b}	1,477^{ab}	1,489^{a}	1,523^{a}
Feed intake, g				
Weeks 3 to 6	2,357^{a}	2,433^{a}	2,342^{a}	2,379^{a}
Weeks 3 to 7	3,514^{a}	3,578^{a}	3,443^{a}	3,471^{a}
Gain:Feed				
Weeks 3 to 6	0.41^{b}	0.42^{ab}	0.44^{a}	0.45^{a}
Weeks 3 to 7	0.39^{b}	0.41^{ab}	0.43^{a}	0.43^{a}

^{a,b,c}Means within rows with uncommon superscripts differ (P < 0.05).

Table 5. *Effects of supplemental soybean oil (0, 3, or 6%) in low (L) and high (H) energy diets on body composition, net energy deposition, utilization of Metabolizable energy, and heat production in broilers at 7 weeks of age (adapted from Nitsan et al., 1997)*

	L0	L3	H3	H6
Dry matter (DM), g/kg	350^{b}	353^{ab}	361^{a}	356^{ab}
Protein, g/kg DM	538^{a}	516^{a}	507^{a}	497^{a}
Ash, g/kg DM	79^{a}	67^{a}	69^{a}	67^{a}
Fat, g/kg DM	419^{a}	461^{a}	438^{a}	458^{a}
Kcal/kg DM	6,071^{a}	6,095^{a}	6,095^{a}	6,166^{a}
Kcal/body[1]	4,015^{b}	4,517^{a}	4,613^{a}	4,541^{a}
Net energy deposition[2], kcal	2,844^{b}	3,346^{a}	3,442^{a}	3,370^{a}
Metabolizable energy utilization	0.28^{b}	0.32^{a}	0.32^{a}	0.31^{a}
Heat production, kcal	5,784^{a}	4,971^{bc}	5,330^{ab}	5,043^{b}

[1]Body energy content of chicks at 3 weeks of age at the beginning of the experiment was 1,171 kcal/body.
[2]Net energy deposition (kcal) = body energy at 7 weeks of age – body energy at 3 weeks of age.
[3]Metabolizable energy utilization = net energy deposition/metabolizable energy intake.
[4]Heat production (kcal) = (feed intake × AMEn) – net energy deposition.
^{a,b,c}Means within rows with uncommon superscripts differ (P < 0.05).

EFFECTS OF SOYBEAN OIL ON MINERAL DIGESTIBILITY

During the lipid digestion process, the release of fatty acids from triglycerides can result in the potential for them to react with divalent minerals to form soluble or insoluble soaps, which may reduce the utilization of fatty ands and minerals in birds (Ravindran et al., 2016). Diets containing high concentrations of calcium may increase the formation of lipophytins (complex of Ca/Mg-phytate, lipids, and peptides), which may reduce the AME value of lipids, especially in animal fats containing high proportions of saturated fatty acids (Ravindran et al., 2016). Several studies have shown that the potential for insoluble soap formation, and subsequent reduction in utilization of fatty acids and minerals is greater with saturated fatty acids compared to lipids containing more unsaturated fatty acids (Atteh and Leeson, 1983; 1984; Atteh et al., 1983; Lin and Chiang, 2010; Tancharoenrat and Ravindran, 2014). Therefore, because soybean oil contains a high proportion of unsaturated fatty acids relative to saturated fatty acids, the potential reduction in fatty acid and mineral digestibility is likely less than when adding more saturated fats to broiler diets.

EFFECTS OF DIETARY SOYBEAN OIL SUPPLEMENTATION ON GROWTH PERFORMANCE AND CARCASS CHARACTERISTICS

Several studies have been conducted to compare the effects of feeding diets containing various dietary levels of supplemental fats and oils on growth performance and carcass characteristics of broilers. Balevi and Coskin (2000) evaluated the growth performance of broilers fed diets supplemented with 5% of various lipid source including sunflower oil, cottonseed oil, corn oil, flaxseed oil, soybean oil, olive oil, fish oil, tallow, and rendering oil in broiler diets during a 49-day feeding period. In this study, birds fed diets containing corn oil, soybean oil, flaxseed oil, tallow, and rendering oil had similar body weight gain during the overall feeding period, but lipid source had no effect on body weights of broilers through day 14 of the feeding period **(Table 6).** A similar pattern of responses was observed for overall average daily feed intake (ADFI) and Feed:Gain (F:G) among these lipid sources, except that feeding the 5% tallow diet resulted in the poorest F:G response **(Table 7).**

Table 6. *Effect of feeding diets containing 5% of various lipid sources on body weights of broilers at various growth stages during a 49-day feeding period (adapted from Balevi and Coskin, 2000).*

Lipid source	Day 1	Day 14	Day 28	Day 42	Day 49
Sunflower oil	48	329	888^{cd}	1,586^{cd}	1,957^{bc}
Cottonseed oil	48	310	907^{bcd}	1,691^{abc}	1,901^{c}
Corn oil	49	304	990^{a}	1,808^{a}	2,197^{a}
Flaxseed oil	49	318	930^{abc}	1,706^{ab}	2,073^{ab}
Soybean oil	51	331	939^{abc}	1,742^{ab}	2,080^{ab}
Olive oil	48	313	952^{ab}	1,639^{bcd}	1,943^{bc}
Fish oil	48	322	785^{e}	1,543^{d}	1,887^{c}
Tallow	49	323	881^{cd}	1,771^{a}	2,074^{ab}
Rendering oil	50	370	869^{d}	1,717^{ab}	2,099^{ab}

Table 7. *Effect of feeding diets containing 5% of various lipid sources on growth performance of broilers during a 49-day feeding period (adapted from Balevi and Coskin, 2000).*

Lipid source	ADG, g	ADFI. g	Feed:Gain
Sunflower oil	38.9	81.2	2.08
Cottonseed oil	37.8	83.9	2.22
Corn oil	43.9	85.6	1.95
Flaxseed oil	41.3	82.1	1.99
Soybean oil	41.4	84.4	2.04
Olive oil	38.7	80.5	2.08
Fish oil	37.5	78.0	2.08
Tallow	41.3	93.3	2.26
Rendering oil	41.8	84.1	2.01

In a similar study, Pesti et al. (2002) compared growth performance and carcass responses from feeding corn-soybean meal diets containing 3% or 6% of eight different lipid sources that varied in fatty acid composition and extent of oxidation to broilers during a 40-day feeding period. Lipid source included two sources of poultry fat, along with restaurant grease, white grease, animal-vegetable blend, palm oil, yellow grease, and soybean oil. Despite differences in AMEn content among these lipid sources, there were no differences in overall growth performance of birds, but increasing the dietary lipid supplementation level from 3 to 6% improved F:G by 3.4 points. Furthermore, feeding the feed-grade poultry fat reduced abdominal fat pad compared with feeding the other lipids sources.

Firman et al. (2008) used a method described by (Sibbald, 1976) to estimate AME values of sources of yellow grease, animal-vegetable blend, soybean oil, poultry fat, lard, palm oil, and tallow. Using these estimated AME values, diets were formulated to contain 3% of each lipid source and fed to broilers for 49 days. Minimal differences were observed for growth performance and carcass composition among dietary treatments, which were similar to those reported by Pesti et al. (2002), suggesting that regardless of differences in AME values among these lipid sources, growth performance and carcass composition was similar.

In contrast to the results reported by Pesti et al. (2002) and Firman et al. (2008), several studies have reported improvements in growth performance, without negatively affecting carcass characteristics, when feeding degummed soybean oil to broilers. Baião and Lara (2005) summarized growth performance and carcass responses from feeding various fats and oils to broilers.

Scaife et al. (1994) fed diets containing beef tallow, soybean oil, canola oil, marine fish oil, or a mixture of these lipids to female broilers. Feeding canola oil resulted in greater feed intake and body weights than soybean oil, but feeding soybean oil resulted in a significant increase in live body weight compared with other lipid sources. Birds fed diets containing beef tallow had the poorest F:G.

Zollitsch et al. (1996) also compared growth performance and carcass characteristics of broilers fed diets containing 3.5% of an animal-vegetable blend, soybean oil, rapeseed oil, or a processed fat product for 43 days. Birds fed the soybean oil and rapeseed oil diets had improved growth performance and had less lipid in excreta than birds fed the animal-vegetable blend and processed fat product, which was assumed to be due to less digestibility of saturated fatty acids of the animal-vegetable blend and processed fat product. There were no differences in the proportion of legs, breast, and abdominal fat, nor differences in dry matter, protein, and fat content of thigh meat or organoleptic characteristics of breast meat among dietary treatments. These researchers concluded that growth performance of broilers can be improved

by feeding relatively high amounts of polyunsaturated fatty acids from soybean oil or rapeseed oil without negatively carcass characteristics.

Vieira et al. (2002) fed diets containing 0, 4, or 8% soybean oil or acidulated soybean oil soapstock and observed similar body weight gain of broilers among sources, but a reduction in feed intake of birds fed acidulated soapstock when the diet inclusion rate was increased from 4 to 8%. However, feeding soybean oil did not result in a reduction in feed intake, but rather improved feed conversion compared with feeding diets containing acidulated soybean oil soapstock.

Similarly, Lara et al. (2003) fed diets containing degummed soybean oil, poultry fat, acidulated soybean oil soapstock, a mixture of poultry fat and soybean oil, or a mixture of soybean oil and acidulated soybean oil soapstock to male broilers. Feeding the soybean oil diets improved body weight gain and feed intake compared with feeding diets containing acidulated soybean oil soapstock. There were no differences in moisture, protein, or lipid content of breast, thigh, and whole carcass of birds fed these lipid sources.

Moura (2003) also reported that supplementing broiler diets with soybean oil had no effect on moisture and lipid content of breast and thigh muscles, and that fat deposition in breast muscle and viscera was not affected by adding soybean oil to the diet. However, Cascabulho (2000) showed that feeding refined or crude soybean oil increased the concentrations of linoleic acid in the carcass of birds compared with feeding acidulated soybean oil.

Barbour et al. (2006) conducted two experiments to evaluate the effects of increasing dietary supplementation of soybean oil to broiler diets containing low ME content on growth performance and carcass composition. In experiment 1, low ME (2,965 kcal/kg) isocaloric and isonitrogenous diets were supplemented with 0, 1, 2, or 3% soybean oil. In experiment 2, diets containing either 2,940 kcal/kg ME or 3,040 kcal/kg ME were supplemented with 0, 2 or 4% soybean oil. Results from experiment 1 showed that adding 2 or 3% soybean oil to the starter diet (1 to 21 days) improved gain:feed (G:F) without affecting body weight gain (data not shown). For the overall 49-day feeding period, body weight gain was improved when feeding 1% and 2% soybean oil diets, but the addition of 3% soybean oil was necessary for improving G:F **(Table 8).** Furthermore, there was a linear increase in "ready-to eat" (RTE) carcass weight by feeding increasing dietary levels of soybean oil, which was greatest at the lowest level of dietary soybean oil supplementation **(Table 8).** Carcass abdominal fat was linearly decreased without affecting breast muscle weight or moisture, protein, and lipid composition of the carcass **(Table 8).** Results from experiment 2, showed that adding 2% soybean oil to either the 2,940 or 3,040 kcal/kg ME diets linearly improved body weight gain during the 21-day starter period (data not shown), but although feeding the 4% diet had no effect on body weight gain during the starter period for the lower ME diet, cumulative body weight gain improved during the overall 49-day feeding period **(Table 9).** However, soybean oil supplementation had no effect on G:F regardless of dietary energy density **(Table 9).** "Ready-to-eat" carcass weight linearly increased with increasing soybean oil supplementation level regardless of dietary energy density **(Table 9),** and abdominal fat was linearly reduced only for broilers fed the 4% soybean oil diet containing 2,940 kcal/kg. Carcass yield, pectoralis major muscle yield, and carcass moisture, protein, and lipid content were not affected by the level of soybean oil addition to diets containing the two dietary ME levels. These results indicate that the addition of 3 or 4% soybean oil to broiler diets containing 2,950 or 3,050 kcal ME/kg improves body weight gain, RTE carcass weight, and reduces carcass abdominal fat without affecting moisture, protein, and lipid content of the carcass.

Table 8. *Effects of increasing dietary levels of soybean oil in low ME (2,965 kcal/kg) diets fed to broilers on growth performance and carcass composition at 49 days of age (adapted from Barbour et al., 2006).*

Measure	Dietary Soybean Oil Supplementation Level, %			
	0	1	2	3
Body weight gain[1], g	1,889	1,967	2,012	2,064
Gain:Feed[1]	0.401	0.403	0.413	0.423
Carcass weight[1,2], g	1,304	1,363	1,376	1,401
Carcass yield[2], %	65.6	66.0	65.7	66.4
Abdominal fat[1], %	2.00	1.61	1.66	1.55
Breast muscle, %	6.34	6.44	6.35	6.48
Carcass moisture[2], %	63.1	63.5	63.6	63.5
Carcass protein[2], %	18.2	18.5	18.2	18.3
Carcass lipid[2], %	13.3	12.8	12.7	12.7

[1]Linear effects of soybean oil supplementation level (P < 0.05).
[2]Ready-to-cook carcass weight and composition.

Table 9. *Effects of increasing dietary levels of soybean oil in broiler diets varying in ME (2,940 kcal/kg or 3,040 kcal/kg) on growth performance and carcass composition at 49 days of age (adapted from Barbour et al., 2006).*

Measure	Dietary ME, kcal/kg					
	2,940[1]			3,040[2]		
	Dietary Soybean Oil, %					
	0	2	4	0	2	4
Body weight gain, g	1,964	2,057	2,093	2,012	2,093	2,123
Gain:Feed	0.435	0.432	0.434	0.452	0.448	0.452
Carcass weight[3], g	1,321	1,386	1,415	1,357	1,461	1,444
Carcass yield[3], %	67.2	67.1	67.0	68.0	68.2	67.5
Abdominal fat, %	1.43	1.17	1.12	1.55	1.41	1.46
Pectoralis major muscle, %	4.83	5.08	5.04	4.56	4.82	4.88
Carcass moisture[3], %	66.0	66.0	66.5	66.0	66.0	66.0
Carcass protein[3], %	17.8	17.9	18.0	18.0	17.6	17.5
Carcass lipid[3], %	12.8	13.0	12.4	13.2	12.9	13.3

[1]Linear effects of soybean oil supplementation level on body weight gain, carcass weight, and abdominal fat (P < 0.05).
[2]Linear effect on body weight gain and carcass weight (P < 0.05).
[3]Ready-to-cook carcass weight and composition.

Azman et al. (2004) evaluated the effects of feeding broiler diets containing 4% soybean oil, poultry grease, beef tallow, or a mixture of soybean oil and poultry grease (SPG) during for 21 days, followed by 6% diet inclusion rate of these respective lipid sources for 22 to 41 days, on growth performance and fatty acid composition of abdominal fat, thigh skin, breast and thigh muscle of broilers. Birds fed the soybean oil diets had greater final body weight and ADG compared with those fed the SPG blend, and birds fed soybean oil or beef tallow had greater ADFI than those fed the other lipid sources. Dietary lipid source substantially altered the fatty acid composition of various portions of the carcass. Broilers fed soybean oil had decreased saturated fatty acids (SFA) in skin and abdominal fat, and increased PUFA (primarily linoleic acid) in skin, abdominal fat, and breast muscle compared with feeding the other lipid sources. In contrast, feeding the beef tallow supplemented diets increased SFA content of thigh skin and abdominal fat pad while decreasing PUFA in skin, abdominal fat, breast, and thigh muscles. Birds fed the poultry grease diets had increased oleic acid content in thigh and breast muscle. These results show that compared with other lipid sources, the addition of soybean oil to broiler diets not only improves growth performance, but also decreases the SFA content and increases the PUFA content of various portions of the carcass. The increased PUFA content in thigh muscle from feeding soybean oil reported in this study (Azman et al., 2004) is similar to the results reported by Crespo and Esteve-Garcia (2001), but less than those reported by Hrdinka et al. (1996). Regard-

less, feeding diets supplemented with soybean oil reduces the SFA content and increases PUFA content of skin, abdominal fat, and breast muscle, which has human health benefits when consuming chicken meat.

EFFECTS OF FEEDING OXIDIZED SOYBEAN OIL ON GROWTH PERFORMANCE, CARCASS CHARACTERISTICS, AND MEAT QUALITY

Feeding oxidized oils to broilers reduces growth performance (Takahashi and Akiba, 1999; Anjum et al., 2004; Tavárez et al., 2011, Hung et al., 2017), which may be attributed to increased oxidative stress (Tavárez et al., 2011; Boler et al., 2012; Hung et al., 2017). Lindblom et al. (2019) evaluated the effects of feeding diets containing 5% fresh (unoxidized) or oxidized (heated at 90°C for 72 hours) palm oil, soybean oil, flaxseed oil, and fish oil on broiler growth performance (4 to 25 days of age) and oxidative stress. Results from this study showed significant differences in growth rate, feed intake, and gain efficiency between oil sources, oxidation, and source × oxidation interactions (Table 10). Diets containing fresh palm, soybean, or flax oil has similar ADG, ADFI, and G:F, which were greater than that observed for fish oil. Feeding oxidized palm, soybean, and flax oil reduced ADG compared with diets containing their respective fresh oil, but feeding oxidized fish oil had no effect on ADG compared with feeding fresh fish oil. Similarly, ADFI was reduced by feeding oxidized soybean oil and flax oil, but oxidation of palm oil and fish oil had no effect of ADFI compared with feeding the respective fresh oils. As a result, feeding oxidized palm, soybean, and flax oil reduced G:F compared with feeding fresh oils, but was unchanged for fish oil. It was surprising that feeding oxidized fish oil had no effect on growth performance compared with feeding fresh fish oil diets, but the lower ADFI for broilers fed fresh fish oil diets compared with other fresh oil sources, which suggests that palatability of diets may have been reduced.

Nutritionists are constantly searching for reliable indicators of oxidation status of oils to predict growth performance of broilers. In the same study, Lindblom et al. (2019) correlated various measures of oil oxidation with growth performance of broilers (Table 11). With the exception of U:S, peroxide value, hexanal, p-anisidine value, and total tocopherols, assays for many of these indicator measurements of lipid oxidation are not commonly available in commercial laboratories. Surprisingly, there were no significant correlations between peroxide value, hexanal, and 4-hydroxynonenal with any of the growth performance measures. Hung et al. (2017) showed that peroxide value was correlated to ADG in broilers. However, p-anisidine value, sum of 11 aldehydes, acrolein, 2,4-decadienal, total polar compounds, and polymerized triglycerides were all negatively correlated with growth performance measures, while the U:S and total tocopherols were positively correlated with growth performance. An increase in U:S of oils is indicative of greater digestibility and energy value, while a decrease in U:S is expected when oils are oxidized because unsaturated fatty acids are more susceptible to oxidation than saturated fatty acids. Furthermore, the positive correlation of total tocopherols with growth performance was expected because oxidation reduces tocopherol content. These results suggest that p-anisidine value, 2,4-decadienal, total polar compounds, and polymerized triacylglycerides should be measured and used as indicators of lipid oxidation status because they were consistently correlated with growth performance.

Table 10. *Effects of feeding diets containing 5% fresh or oxidized palm, soybean, flax, and fish oil on growth performance of broilers from 4 to 25 days of age (adapted from Lindblom et al., 2019)*

	Palm oil		Soybean oil		Flax oil		Fish oil	
	Fresh	Oxidized	Fresh	Oxidized	Fresh	Oxidized	Fresh	Oxidized
ADG, g	46.8^{a}	40.7^{b}	47.0^{a}	36.0^{c}	47.3^{a}	36.5^{c}	34.0^{c}	34.5^{c}
ADFI, g	56.5^{ab}	52.8^{b}	57.4^{a}	48.1^{c}	56.1^{ab}	49.0^{c}	46.9^{c}	46.4^{c}
G:F	0.829^{a}	0.769^{b}	0.819^{a}	0.749^{bc}	0.845^{a}	0.744^{bc}	0.726^{c}	0.746^{bc}

^{a,b,c}**Means with different superscripts within row are different (P < 0.05).**

Table 11. *Correlation coefficients between measures of oil composition and oxidation products1 and growth performance measures (adapted from Lindblom et al., 2019)*

	UFA:SFA	AnV	TALD	ACR	DDE	TPC	PTAGS	TOC
ADG	0.32	-0.59	-0.37	-0.61	-0.31	-0.49	-0.50	0.52
ADFI	0.27	-0.60	-0.30	-0.62	-0.29	-0.45	-0.47	0.50
G:F	0.33	-0.42	-0.36	-0.47	-0.27	-0.42	-0.43	0.42

[1]UFA:SFA = unsaturated to saturated fatty acid ratio; AnV = p-anisidine value; TALD = sum of 11 aldehydes; ACR = acrolein; DDE = 2,4-decadienal; TPC = total polar compounds; PTAGS = polymerized triglycerides; TOC = total tocopherols.

Lindblom et al. (2019) also evaluated oxidative stress indicators by collecting plasma and liver samples of broilers fed fresh and oxidized oils and analyzing them for thiobarbituric acid reactive substances (TBARS), protein carbonyls, 8-hydroxy-2'-deoxyguanosine (8-OH-2dG), glutathione peroxidase (GPx), superoxide dismutase, and catalase activity. Plasma 8-OH-2dG concentrations were increased by feeding oxidized oils, and plasma GPx activity was decreased by feeding oxidized oils except for fish oil. Liver TBARS concentration was greater in broilers fed oxidized palm oil compared with fresh palm oil, and liver protein carbonyls were similar among broilers fed fresh or oxidized palm, flaxseed, and fish oil, but were increased for birds fed oxidized soybean oil compared to fresh soybean oil. These results indicate that feeding 5% oxidized palm, soybean, flax and fish oil can increase oxidative stress to a differing magnitudes in broilers.

Anjum et al. (2004) also evaluated the effects of feeding 2% fresh soybean oil (3 mEqO2/kg and acid value of 2.52 mg/g of oil) and 2% oxidized soybean oil (50mEqO2/kg and acid value of 7.26 mg/kg) in broiler starter (0 to 4 weeks) and finisher (5 to 6 weeks) phases on growth performance, organ weights and meat quality. Compared with feeding fresh oil, diets containing oxidized soybean oil reduced ADG during the starter period and the overall 6-week feeding period, but there were no significant effects on ADFI in each phase or overall (Table 12). As a result, overall F:G was poorer for birds fed oxidized soybean oil. There was no difference in carcass yield between dietary treatments or organ weights except that liver weight (g/bird and per 100 g of live weight) was increased for broilers fed oxidized soybean oil. An increase in liver weight is a consistent indicator resulting from feeding oxidized oils because of the need to detoxify dietary aldehydes and other oxidation compounds (Cherian et al., 1996; Wang et al., 1997, Waheed et al, 2004). Furthermore, thiobarbituric acid (TBA) content was increased in livers of broilers fed oxidized soybean oil compared to those fed fresh oil, but there were no differences in TBA content of muscle. The negative effects of feeding oxidized soybean oil in this study were less dramatic than those observed by Lindblom et al. (2019), which was likely due to differences in the extent of soybean oil oxidation and a lower diet inclusion rate of soybean oil. Nevertheless, minimizing soybean oil oxidation should be a high priority when using it in broiler diets to avoid suboptimal growth performance and health of birds.

Table 12. *Effects of feeding diets containing 2% fresh or oxidized soybean oil to broilers on growth performance from 0 to 6 weeks of age (adapted from Anjum et al., 2004)*

	Fresh soybean oil	Oxidized soybean oil
Starter (0 to 4 weeks of age)		
ADG, g	1,029[a]	983[b]
ADFI, g	1,717	1,687
Feed:Gain	1.67	1.72
Finisher (5 to 6 weeks of age)		
ADG, g	722	695
ADFI, g	1,859	1,838
Feed:Gain	2.57	2.64
Overall (0 to 6 weeks of age)		
ADG, g	1,751[a]	1,678[b]
ADFI, g	3,576	3,526
Feed:Gain	2.04[a]	2.10[b]
Mortality, %	2.0	6.0

[a,b]Means with different superscripts within row are different (P < 0.05).

BENEFITS OF SOYBEAN OIL IN BROILER DIETS UNDER HEAT STRESS CONDITIONS

Heat stress has negative effects on broiler welfare, growth performance, and reduces natural immunity and resistance to diseases in most countries around the world. Seifi et al. (2018) evaluated responses from feeding diets containing 3%, 6%, or 9% olive oil, soybean oil, coconut oil or beef tallow on mitochondrial energetics of heat-stressed broilers. Results from this study showed that saturated fatty acids from more saturated lipid sources may be more effective in reducing the metabolic heat load in birds subjected to heat stress compared with lipid sources containing greater amounts of unsaturated fatty acids.

Htin et al. (2007) evaluated the effects of feeding diets containing 8% palm oil (about the same proportion of saturated and unsaturated fatty acids), coconut oil (high in saturated fatty acids), soybean oil (high in n-6 polyunsaturated fatty acids), and fish oil (high in n-3 polyunsaturated fatty acids) on growth performance of broilers under heat stress conditions. Results from this study showed that feeding 8% palm oil improved body weight on day 42, and reduced mortality rate compared with feeding diets containing 8% soybean oil, coconut oil, or fish oil.

Ali et al. (2001) conducted a study to determine the effects of feeding diets containing 0, 2, 4, 8, or 10% soybean oil to broilers (30 days of age) exposed to 28 to 33°C temperatures during a 15-day finisher period on growth performance. Results from this study showed that body weight gain and F:G improved by the addition of soybean oil up to 10% of the finisher diet, but was optimized at the 4% and 6% diet inclusion rates (Table 13). These results suggest that the addition of soybean oil to broiler diets can be effective in alleviating the negative effects on growth performance in finisher broilers raised under heat stress conditions.

Table 13. *Effects of increasing dietary soybean oil level of growth performance of finisher broilers (30 to 45 days of age) raised under heat-stress conditions (28 to 33°C; adapted from Ali et al., 2001)*

Measure	Dietary Soybean Oil Supplementation Level, %					
	0	2	4	6	8	10
Initial body weight, g	1,212	1,214	1,214	1,212	1,214	1,215
Final body weight, g	1,976^{a}	2,084^{c}	2,134^{d}	2,173^{e}	2,081^{c}	2,049^{b}
Body weight gain, g/15 d	764^{a}	870^{b}	920^{c}	961^{d}	867^{b}	782^{a}
Feed intake, g/15 d	2,423^{a}	2,418^{a}	2,367^{ab}	2,311^{b}	2,285^{bc}	2,222^{c}
Feed:Gain	3.17^{a}	2.76^{b}	2.57^{c}	2.41^{c}	2.64^{a}	2.84^{d}

POTENTIAL BENEFITS OF ADDING SOYBEAN OIL TO BROILER DIETS TO MINIMIZE ADVERSE EFFECTS OF AFLATOXINS

Several studies have shown that increased dietary concentrations of protein (Smith et al., 1971), α-tocopherol, ascorbic acid (Hoehler and Marquardt, 1996), pyridoxine, folic acid, riboflavin, choline (Johri et al., 1990), and selenium (Burguera et al., 1983) can be effective in minimizing the adverse effects of aflatoxin contamination in poultry diets. Because aflatoxins have been shown to decrease pancreatic secretions of lipase and bile, which subsequently reduces lipid digestion in poultry (Osborne and Hamilton, 1981), the addition of supplemental lipids may be useful for ameliorating this negative effect. Evidence for the potential beneficial effect of supplemental oils on alleviating minimizing reductions in growth performance and livability from feeding aflatoxin contaminated diets has be reported when diets containing 16% olive oil or sunflower oil were fed (Smith et al., 1971), and the extent of lipid unsaturation appears to affect the magnitude of toxic effects caused by aflatoxins (Smith et al., 1971). Furthermore, the minimum toxic concentration of aflatoxins was reported to be greater in diets containing 18% supplemental lipids (Richardson et al., 1987). However,

studies showing beneficial effects of lipid supplementation on reducing the negative effects of aflatoxins have required the addition of high dietary inclusion rates of lipids to achieve these responses, which is problematic in feed mixing, pelleting, and handling. Therefore, Raju et al. (2005) conducted a study to evaluate the effects of adding 3% or 6% sunflower oil, soybean oil, or groundnut oil in isocaloric and isonitrogenous diets containing none or 0.3 μg of aflatoxin B1/g to broilers from 0 to 42 days of age. Body weight gain and feed intake were reduced when feeding aflatoxin contaminated diets, but the addition of 3% soybean to the aflatoxin contaminated diet resulted in similar growth performance compared with birds fed the control diets (Table 14). A similar response was observed when feeding the 3% sunflower oil diets but not when feeding the groundnut oil diets. Furthermore, feeding the aflatoxin contaminated diets reduced serum concentrations of cholesterol and triglycerides, and increased liver, pancreas, gall bladder, and giblet weights, as well as liver lipid content. Supplementing diets with any of these 3 oils alleviated these negative effects. Supplemental soybean oil or sunflower oil improved the humoral immune response, which was depressed when feeding the aflatoxin diets without supplemental oils. These results indicated that adding 3% soybean or sunflower oil is effective in alleviating the adverse effects caused by feeding diets containing 0.3 μg aflatoxin B1/g of diet in broilers.

Table 14. *Effects of adding 3% soybean oil to aflatoxin contaminated (0.3 ppm) broiler diets on growth performance up to 42 days of age (adapted from Raju et al., 2005)*

	Control	3% soybean oil	0.3 ppm aflatoxins	3% soybean oil + 0.3 ppm aflatoxins
Body weight, kg	2.12[a]	2.14[a]	1.85[b]	2.05[a]
Feed intake, kg	3.79[a]	3.91[a]	3.39[b]	3.74[a]
Feed: Gain	1.88	1.83	1.84	1.83

EFFECTS OF DIETARY SOYBEAN OIL IN DIETS FOR BROILER BREEDERS

There is very little published information on the role of soybean oil supplementation in diets of broiler breeder hens on subsequent embryonic development, health, hatchability, and chick viability. The oocyte or egg yolk contains about 50% water 17% protein, and 33% lipids (Cherian, 2005). The lipids in egg yolk are in the form of lipoproteins, and triacylglycerides represent about 65% and phospholipids comprise about 28% of total lipids in eggs (Cherian, 2015). Greater than 88% of triacylglycerol and 95% of phospholipids are utilized by the growing chick embryo during the 21-day incubation period (Cherian, 2015). Triacyglycerols are the major source of energy for the embryo, while phospholipids serve as precursors for structural lipids in membrane bilayers (Speake et al., 1998), and store long-chain (> 20 carbon) PUFAs, such as arachidonic acid (20:4n-6) and docosahexanenoic acid (DHA, 22:6 n-3). Because the nutrients present in the egg serve as the sole source of energy and nutrients for the developing embryo, any deficiency of nutrients can have detrimental effects on subsequent growth, health, tissue maturation, and immune status of chicks (Cherian, 2015).

Essential n-3 (α-linoleic acid; 18:3 n-3) and n-6 (linoleic acid; 18;2 n-6) fatty acids are required and must be supplied in the diet for optimal embryonic development. In the liver, α-linoleic acid is converted to eicopentaenoic acid (EPA, 20:5 n-3), which is subsequently converted to docopentaenoic acid (DPA, 22;5 n-3) and docosahexanenoic acid (DHA, 22:6 n-3; Brenner, 1971). The same pathway is used to convert linoleic acid to produce arachidonic acid (20:4 n-6). However, although n-3 and n-6 PUFAs share the same metabolic pathways, they provide different and sometime opposite biological effects.

Soybean oil is comprised of high concentrations of n-6 PUFAs, but contains very low concentrations of n-3 PUFAs, compared with flax, canola, and fish oils, which are commonly used as n-3 fatty acid sources in poultry diets (Cherian, 2015). Poultry diets generally contain high concentrations of n-6 PUFAs and low concentrations of n-3 PUFAs. Increased dietary DHA content is associated with improvements in animal growth, fertility, immunity, and bone strength in pigs and poultry (Lee et al., 2019). Therefore, the ultimate goal for optimizing lipid composition in developing chick embryos is to achieve the proper balance of n-6 and n-3 fatty acids. However, more research is needed to determine the optimal dietary ratio of n-3 and n-6 PUFAs in broiler breeder hen diets to optimize embryonic development, health, immune status and subsequent growth performance of broiler chicks.

SUMMARY

Soybean oil generally contains the greatest AME content for broilers among all common fats and oils because of its high PUFA content, low MIU and FFA content. However, estimates of AME content of soybean oil vary because of several factors including age of the bird, U:S and FFA content, fatty acid chain length, fatty acid position on glycerol of triglycerides, and MIU content. Because of the variability in AME estimates for soybean oil, and the lack of accurate AME prediction equations, overestimation of actual AME content can lead to suboptimal growth performance. Some published studies have shown minimal differences in growth performance and carcass characteristics between broilers fed diets containing soybean oil compared with other lipid sources, while several other studies have shown growth and carcass composition benefits from supplementing diets with soybean oil, especially when it is not oxidized. Several studies have shown that lipid source affects the fatty acid profile of skin, abdominal fat, and muscle of broiler carcasses, where feeding soybean oil diets generally increase PUFA content and reduce saturated fatty acid content of these tissue compared to feeding saturated animal fats. Differences in growth performance responses among published studies are likely a result of the accuracy or inaccuracy of AME values and the magnitude of oxidation of the soybean oil sources used in diet formulations of these studies. Soybean oil provides an "extra caloric effect" because it often results in greater improvement in growth rate and feed conversion above that predicted from its energy content. However, because of its relatively high PUFA content, it may have a greater negative impact mineral digestibility, and may not be as effect as more saturated lipid sources in alleviating the negative effects of heat stress. One of the interesting "value-added" features of soybean oil is that there is some evidence suggesting that adding 3% soybean or sunflower oil to broiler diets containing 0.3 μg aflatoxin B1 is effective in alleviating the adverse effects of aflatoxins in broilers.

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Chapter

10

Feeding Applications of U.S. Soybean Oil in Layer Diets

INTRODUCTION

U.S. degummed soybean oil has been shown to contain the highest AMEn content for laying hens among many of the common fats and oils market (Murugesan et al., 2017). Supplemental fats and oils are commonly added to diets for laying hens to increase energy density, improve absorption of vitamins, and improve egg yield and weight of eggs and yolk (Whitehead, et al., 1991). Supplementing layer diets with soybean oil has been shown to increase egg production performance and egg quality, and is effective in restoring feed intake of some genetic lines of layers under heat stress conditions (Açikgöz et al., 2002). Furthermore, adding soybean oil to layers diets increases linolenic and docosahexaenoic acid content of egg yolks, which have been shown to have beneficial health effects for humans consuming eggs (Dänicke et al., 2000). Unfortunately, a limited number of studies have been conducted to evaluate the effects of adding soybean oil to layer diets compared with numerous studies conducted with broilers. The purpose of this chapter is to described the most current research on determining energy content of soybean oil for laying hens, and the effects of feeding increasing dietary levels of soybean oil on egg production performance, egg quality, fatty acid composition of egg yolks, reproductive performance, and effects on alleviating heat stress in white and brown genetic lines of laying hens.

METABOLIZABLE ENERGY CONTENT OF SOYBEAN OIL FOR LAYERS

Limited studies have been conducted to determine the AMEn and TME content of soybean oil for layers. The NRC (1994) provided references and values for the AMEn content of crude soybean oil for broiler chicks ranging from 8,020 to 8,795 kcal/kg, and TME of 9,510 kcal/kg for crude soybean oil. Rostagno (2017) indicated that the ME value for soybean oil for layers is 8,790 kcal/kg, with a net energy value of 7,911 kcal/kg. Sauvant et al. (2002) indicated AMEn values of soybean oil for cockerels and broilers were 9,100 and 9,004 kcal/kg, respectively.

More recently, Irandoust et al. (2012) determined the AMEn content of crude soybean oil, recycled soybean oil, and soybean acid oil fed to laying hens to be 9,127 kcal/kg, 8,948 kcal/kg, and 7,966 kcal/kg, respectively. Murugesan et al. (2017) determined the AMEn content of U.S. soybean oil and 9 other lipid sources in Ross 308 broilers (21 days of age), Hybrid XL turkeys (21 days of age), and Hy-Line W36 laying hens (60 weeks of age). The AMEn content of soybean oil ranged from 7,288 kcal/kg in turkeys, to 9,320 kcal/kg in layers, while the AMEn content of soybean oil for broilers was intermediate at 8,123 kcal/kg. Furthermore, the AMEn content of U.S. soybean oil for layers was greater than choice white grease (8,249 kcal/kg), corn oil (7,686 kcal/kg), distillers corn oil (6,483 and 8,284 kcal/kg for two sources), poultry fat (6,986 kcal/kg), and 3 sources of animal-vegetable blends (5,257, 5,516, and 6,045 kcal/kg). These results show that there are substantial differences in AMEn content among bird species and lipid sources, but U.S. soybean oil provided the greatest energy value for layers in this study. Based on these recent results, it appears that a value of 9,100 to 9,300 kcal/kg AMEn can be used for diet formulation when adding U.S. soybean oil to layer diets.

PRODUCTION PERFORMANCE, EGG QUALITY, FATTY ACID COMPOSITION OF EGG YOLK, AND REPRODUCTIVE PERFORMANCE OF LAYERS FED SOYBEAN OIL

Limited studies have been conducted to evaluate the addition of soybean oil to layer diets on egg production performance. Lelis et al. (2009) fed diets containing 0%, 2%, or 4% soybean oil, canola oil, linseed oil, and fish oil to Hy Line W36 (light birds) and Hy Line Brown (heavy birds) during four 28-day production periods of the second production cycle. Light layers had less feed intake and improved feed conversion compared to heavy layers, but lipid source and diet inclusion rate had no effect on feed intake. Furthermore, lipid source and diet inclusion rate had no effect on percentage egg production, egg weight, egg mass, and feed conversion in this study.

In contrast, Costa et al. (2008) showed that feeding increasing dietary levels of soybean oil linearly increased egg production compared with no effect from feeding canola oil supplemented diets. Similarly, Rodrigues et al. (2005) showed an improvement in egg production as diet inclusion rates of soybean oil increased, and performance was maximized at the 8% diet inclusion rate. Rabello et al. (2003) showed that layers fed diets containing 3% soybean oil has increased egg weight, but studies conducted by Rodrigues et al. (2005) and Maramatsu et al. (2005) showed no improvement in egg weight by feeding increasing dietary levels of soybean oil. Similar to the responses reported by Lelis et al. (2009), other studies have reported no effect of dietary soybean oil supplementation level on feed intake (Muramatsu et al., 2005; Rodrigues et al., 2005; Costa et al., 2008). Muramatsu et al. (2005) and Rodrigues et al. (2005) also reported no effect of dietary soybean oil levels on feed conversion of laying hens.

Dänicke et al. (2000) conducted a comprehensive study to evaluate the effect of dietary soybean oil supplementation level (0%, 3.5%, 7%, 10.5%, and 14%) on prececal nutrient digestibility, egg production performance, egg quality, and fatty acid composition of yolk fat, and reproductive performance in layers at 22 to 45 weeks of age. All diets fed in this study were isocaloric. The addition of increasing dietary levels of soybean oil resulted in increased lipid and fatty acid digestibility **(Table1),** but did not affect protein and amino acid digestibility. The negative apparent digestibility values for palmitic, stearic, and oleic acids were observed for birds fed the unsupplemented diet, which indicates endogenous losses of fatty acids exceeded the amount digested and absorbed. These differences in improved digestibility among fatty acids were likely due to the advantages of fatty acid polarity and melting point, as well as fatty acid position on triacylglycerides in soybean oil compared with other lipid sources (Dänicke et al., 1997).

Egg production and feed intake were not affected by dietary level of soybean oil, but egg weight and daily egg mass improved non-linearly, and body weight increased with increased diet inclusion rates (Dänicke et al., 2000; **Table 2**). Feed conversion was improved when diets contained between 3.5% to 10.5% soybean oil. Increasing dietary levels of soybean oil increased egg weights while increasing the proportion of albumen and decreasing the percentage of yolk and shell weight (Dänicke et al., 2000; **Table 3**). These results are in agreement with those reported from several studies showing that feeding low lipid diets decreases egg weight (Combs and Helbacka, 1960; Bragg et al., 1973; Vogtmann et al., 1973; Whitehead et al., 1993).

Numerous studies have shown that the fatty acid profile of yolk fat can be altered by changing the dietary fatty acid profile (Lall and Slinger, 1973; Pankey and Stadelman, 1969; Guenter, et al., 1971; Couch and Saloma, 1973; Sim et al., 1973; Cherian and Sim, 1991; Cherian et al., 1995; Herber and van Elswyk, 1996; Latour et al., 1998; Scheider et al., 1998). Studies have shown that feeding lipids rich in

omega-3 fatty acids improve circulating omega-3 fatty acids in blood of humans consuming these eggs, which is widely considered as a health benefit (Farrell, 1992; 1993; Farrell and Gibson, 1991).

Dänicke et al. (2000) showed that the proportions of palmitic acid (C16:0), oleic acid (C18:1), linoleic acid (C18:2 n-6), linolenic acid (C18:3 n-3), and docosahexaenoic acid (C22:6 n-3) increased in yolk fat with increasing soybean oil additions **(Table 4).** The increase in n-3 fatty acids (linolenic and docosahexaenoic acids) in egg yolk has a positive effect on improving nutritional value of eggs for humans (Ferrier et al., 1994; Shafey and Cham, 1994; Farrell, 1994). Furthermore, Dänicke et al. (2000) calculated that the maximum deposition efficiency of essential fatty acids from soybean oil in egg yolk is achieved at a dietary inclusion rate of about 7%. However, Balevi and Coskin (2000) fed diets containing 2.5% of soybean oil and 8 other lipid sources to laying hens during a 56-day feeding period and reported no differences in daily feed intake, egg yield and weight, and shell quality, but feeding flax oil increased omega-3 fatty acid content, and feeding soybean oil increased omega-6 fatty acid content of egg yolks compared to other lipid sources.

The fatty acid profile of chicken embryo brain and brain phospholipids can also be modified by the dietary fatty acid profile (Cherian and Sim, 1991; Cherian and Sim, 1992). However, the importance of changes in egg yolk or embryo fatty acid profile on reproductive performance are unknown because a limited studies have shown no effect of dietary lipid level or fatty acid profile on hatchability or fertility (Lall and Slinger, 1973). Dänicke et al. (2000) reported no differences in reproductive performance measures, including percentage of fertilized eggs, hatchability, and chick mortality with increasing dietary inclusion rates of soybean oil **(Table 5).** Overall, these results show that soybean oil can be used effectively in laying hen diets without adversely affecting egg production performance, while improving egg weight and yolk fatty acid profile.

Table 1. *Effect of dietary soybean oil supplementation level on prececal digestibility of gross energy, crude fat, and selected fatty acids in laying hens from 22 to 46 weeks of age (adapted from Dänicke et al., 2000)*

Measure, %	0%	3.5%	7.0%	10.5%	14.0%
Gross energy	79.5	76.9	79.7	80.0	79.4
Crude fat	44.2	73.8	84.5	88.5	91.5
Palmitic acid (C16:0)	-67.4	28.4	56.1	71.2	78.1
Stearic acid (C18:0)	-166.3	71.2	80.4	85.2	89.8
Oleic acid (C18:1)	-47.8	71.2	80.4	85.2	89.8
Linoleic acid (C18:2)	55.6	94.6	96.7	96.5	97.4

Table 2. *Effect of dietary soybean oil supplementation level on egg production performance of laying hens from 22 to 46 weeks of age (adapted from Dänicke et al., 2000)*

Measure, %	0%	3.5%	7.0%	10.5%	14.0%
Feed intake, g/day	119.1	119.7	121.3	118.1	121.9
% egg production	93.6	93.4	93.9	92.9	91.7
Egg weight, g	62.2	65.1	65.9	65.9	66.7
Egg mass, g/hen/day	58.1	60.6	61.9	61.1	61.1
Feed conversion, g/g egg mass	2.08	2.00	1.98	1.96	2.02
Body weight change, g/hen	71	191	267	304	327

Table 3. *Effect of dietary soybean oil supplementation level on egg quality of laying hens from 22 to 46 weeks of age (adapted from Dänicke et al., 2000)*

Measure, %	0%	3.5%	7.0%	10.5%	14.0%
Egg weight, g	63.1	65.8	67.6	66.9	70.1
Yolk, %	25.2	25.0	24.3	24.1	23.4
Shell, %	11.1	10.8	10.5	10.4	10.3
Albumen, %	63.8	64.2	65.2	65.5	66.3
Rochefan yolk color	0.0	1.00	1.5	2.2	2.7
Breaking strength, kp	3.24	3.31	3.12	3.03	2.92

Table 4. *Effect of dietary soybean oil supplementation level on fatty acid composition of yolk fat from laying hens from 22 to 46 weeks of age (adapted from Dänicke et al., 2000)*

Measure, %	0%	3.5%	7.0%	10.5%	14.0%
Myristic acid (C14:0)	0.42	0.34	0.26	0.20	0.17
Myristoleic acid (C14:1)	0.14	0.06	0.03	0.01	0.01
Palmitic acid (C16:0)	24.7	22.2	19.5	18.3	17.3
Palmitoleic acid (C16:1)	5.69	2.77	1.36	0.96	0.72
Stearic acid (C18:0)	6.46	6.94	7.18	6.95	6.71
Oleic acid (C18:1)	44.8	36.8	32.1	30.4	29.6
Linoleic acid (C18:2 n-6)	5.89	17.3	25.7	29.0	31.1
Linolenic acid (C18:3 n-3)	0.30	1.25	2.00	2.30	2.47
Arachidonic acid (C20:4 n-6)	0.79	0.92	1.07	1.12	1.16
Docosahexaenoic acid (C22:6 n-3)	0.38	0.67	0.77	0.78	0.77

Table 5. *Effect of dietary soybean oil supplementation level on fertility and reproductive performance of laying hens from 22 to 46 weeks of age (adapted from Dänicke et al., 2000)*

Measure, %	0%	3.5%	7.0%	10.5%	14.0%
Eggs fertilized, %	95.6	94.5	93.2	94.6	91.7
Chick stuck at hatch, % of fertilized eggs	6.8	6.8	8.7	7.7	15.8
Dead chicks, % of fertilized eggs	4.6	4.3	2.0	3.4	2.0
Chicks hatched, %	84.9	84.7	83.4	83.8	77.0
Chicks hatched, % of fertilized eggs	88.5	89.0	89.3	88.8	82.2

HEAT STRESS

When laying hens are exposed to excessive heat, feed intake decreases (Nir, 1992; Daghir, 1995; Leeson and Summers, 1997) resulting in reduced egg production and egg quality (Deaton, 1983; Leeson, 1986). Increasing energy density of the diet by adding supplemental lipids has been shown to be an effective means of improving diet palatability which promotes improved feed intake, and minimizing body heat production during exposure to excessive high environmental temperatures (Leeson and Summers, 1997). Furthermore, the addition of vegetable oils (i.e. soybean oil) to layer diets has been shown to be more effective than adding animal fats for increasing egg weights, which has been attributed to the high linoleic content of vegetable oils (Whitehead, 1999).

Açikgöz et al. (2002) fed isocaloric and isonitrogenous diets containing 0, 2, or 4% soybean oil to white and brown laying hens housed at temperatures of a maximum of 32.7 °C and 70% relative humidity (minimum temperature and relative humidity was 22.2 °C and 38.5%, respectively), to determine effects of soybean oil supplementation on layer performance and egg quality. White layers had greater egg production, feed conversion, and egg Haugh units, but lower feed intake, egg weight, and shell weight per unit of surface area than brown layers. It is interesting that there was a significant layer strain by soybean oil supplementation level interaction where there was no difference in daily feed intake between white and brown layer strains when fed to control diet (0% soybean oil), but the addition of 2% or 4% soybean oil to brown layer diets increased feed intake compared to adding soybean oil to white layer diets **(Table 6).** Soybean oil supplementation level did not affect egg production of white layers, but the addition of 2% soybean oil to the brown layer diet tended to result in greater egg production than feeding the 4% soybean oil diet. These results suggest that the egg production responses to supplemental soybean oil under heat stress conditions vary among genetic lines of layers, but can improve feed intake for brown layers.

Table 6. *Effects of feeding diets containing 0, 2, or 4% soybean oil to white and brown laying hens during heat stress conditions (32.7 °C and 70% relative humidity) feed intake and egg production (adapted from Açikgöz et al., 2002)*

Measure, %	0% Soybean oil	2% Soybean oil	4% Soybean oil
Feed intake, g/hen/day			
White layers	94.3^{bc}	86.8^{c}	96.3^{b}
Brown layers	99.0^{b}	113.9^{a}	109.5^{a}
Egg production, number/hen/week			
White layers	4.94^{a}	4.67^{ab}	4.86^{ab}
Brown layers	4.64^{bc}	4.90^{ab}	4.37^{c}

^{a,b,c}**Means within columns with uncommon superscripts are different (P < 0.05).**

SUMMARY

Research studies have clearly demonstrated that U.S. degummed soybean oil has been has the highest AMEn content for laying hens among many of the common fats and oils market. Adding increasing dietary levels of soybean oil to layer diets has been shown to increase egg production performance and egg quality, and is effective in restoring feed intake of some genetic lines of layers under heat stress conditions. Furthermore, adding soybean oil to layer diets increases linolenic and docosahexaenoic acid content of egg yolks, which have been shown to have beneficial health effects for humans consuming eggs, and supports satisfactory reproductive performance.

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Chapter

11

Benefits of Feeding High Quality U.S. Soybean Oil on Swine and Poultry Health

INTRODUCTION

There is significant interest in the global feed and animal industry to understand the role of various nutritional components and feed additives with immunomodulation properties to enhance immune function and resistance to viral, bacterial, and protozoan disease challenges (Korver, 2012). It is widely recognized that multiple stressors are involved in intensive poultry and pig production systems that negatively affect metabolic status and health of animals (Gallois et al., 2009). However, the addition of certain dietary sources of fatty acids has been shown to have multiple benefits for improving the immune status and disease resistance in pigs and poultry.

Diets containing high concentrations of n-3 polyunsaturated long-chain fatty acids (n-3 PUFAs) not only enhance the n-3 PUFAs in meat and eggs to provide health benefits for human consumers (Pietras and Orczewska-Dudek, 2013; Yanovych et al., 2013; Zdunczyk and Jankowski, 2013), but are also one of the most effective nutritional approaches to modulate immune function in pigs and poultry (Calder, 2001). The beneficial effects of dietary fatty acids appear to be associated with many molecular metabolic mechanisms including the synthesis of eicosanoids and cytokines, which are involved in mediating inflammatory responses, as well as T lymphocyte signaling (Calder, 1998; Miles and Calder, 1998; Calder, 2003; Stulnig, 2003; Stulnig and Zeyda, 2004; Fritsche, 2006; Komprda, 2012; Benderska-Lojewska et al., 2013). Achieving the optimal dietary balance of n-6:n-3 PUFAs is also important for desired immune function in animals because a high n-6:n-3 PUFA can lead to an increase in production of pro-inflammatory cytokines, such as tumor necrosis factor α (TNFα), interleukin-1 (IL-1), and interleukin-6 (IL-6), which enhance inflammatory responses (Simopoulos, 2002), and reduce feed intake (Klasing, 1988; Ferket and Gernat, 2006).

The addition of fats and oils, including soybean oil, to swine and poultry diets also can also provide significant reductions in dust in confinement facilities. A reduction in respirable dust not only reduces physical irritation to the respiratory tract of animals and humans, but it also reduces the inhalation of pathogens and gases that can further compromise animal health. Therefore, this chapter summarizes the role of soybean oil in enhancing immune system and health benefits in pigs and poultry.

Table 1. *Comparison of fatty acid composition of common lipid sources fed to pigs and poultry (adapted from Swiatkiewicz et al., 2015)*

Lipid	Major fatty acids	%	n-6:n-3
Sunflower oil	C18:1 C18:2 n-6 C18:3 n-3	18 65 0.5	130
Corn oil	C16:0 C18:1 C18:2 n-6 C18:3 n-3	13 32 45 1.0	45
Lard	C16:0 C18:0 C18:1 C18:2 n-6 C18:3 n-3	25 14 42 10 0.5	20
Soybean oil	C18:1 C18:2 n-6 C18:3 n-3	22 52 10	5.2
Rapeseed oil	C18:1 C18:2 n-6 C18:3 n-3	56 22 10	2.2
Flaxseed oil	C18:1 C18:2 n-6 C18:3 n-3	20 16 53	0.30
Fish oil	C16:0 C16:1 C18:1 C18:2 n-6 C18:3 n-3 C20:4 n-6 C20:5 n-3 C22:5 n-3 C22:6 n-3	18 11 12 1.5 1.0 1.0 15 2.0 9	0.10

EFFECTS OF DIETARY SOYBEAN OIL ON IMMUNE RESPONSES OF POULTRY

Although soybean oil contains a relatively low concentration of n-3 PUFAs compared with flaxseed oil and fish oil, it has a more favorable n-6:n-3 than found in sunflower oil, corn oil, and lard **(Table 1).** Unlike other common oil sources rich in n-3 fatty acids, only 3 studies have evaluated the immune responses from feeding soybean oil to broilers (Swiatkiewicz et al., 2015). Results from these studies showed inconsistent responses from feeding soybean oil diets on antibody titers against Newcastle disease **(Table 2).** Unfortunately, no studies have been conducted to evaluate feeding soybean oil to layers on immune responses.

Table 2. *Summary of immune responses from feeding soybean oil to broilers (adapted from Swiatkiewicz et al., 2015)*

Lipid source	Diet inclusion rate	Responses evaluated	Results	Reference
Soybean oil	0, 2, or 4%	Immune response of birds vaccinated for Newcastle disease and infectious bursal disease	Increased heterophil:lymphocyte, reduced Fabricus bursa and spleen, reduced titers against Newcastle disease and infectious bursal disease viruses	Sadeghi et al. (2013)
Soybean, olive, or fish oil	2.15% to 3%	Humoral immune response and IFN-γ gene expression	Increased IFN-γ gene expression and antibody expression against Newcastle disease when fed fish oil. Soybean oil resulted in highest growth performance	Sadeghi et al. (2014)
Soybean, linseed, or sardine oil	7%	Immune response in non-vaccinated and vaccinated birds for Newcastle disease	Increased antibody production in vaccinated birds fed soybean oil containing high levels of n-6 PUFA. No effect of oil source on cellular immune response (lymphocyte proliferation)	Pinto et al. (2014)

EFFECTS OF DIETARY SOYBEAN OIL ON IMMUNE RESPONSES OF SWINE

Similar to poultry, a limited number of studies have been conducted to evaluate the effects of feeding soybean oil on immune responses for swine. Duan et al. (2014) formulated growing-finishing pig diets to contain ratios of n-6:n-3 of 1:1, 2.5:1, 5:1, or 10:1 using soybean and linseed oil added at 3% of the diet, and measured indicators of immune responses. Results showed that pigs fed diets with a 1:1 ratio of n-6:n-3 had reduced serum concentrations of IL-6 and IL-1β inflammatory cytokines, and gene expression of IL-6, IL-1β, and TNF-α mRNA in skeletal muscle and adipose tissue was down regulated.

Park et al. (2009) evaluated growth performance, carcass characteristics, and immune status of growing-finishing pigs fed soybean oil as a partial or complete replacement for tallow (4 to 5% inclusion rates). Results from this study showed that soybean oil can be substituted for tallow in grower-finisher diets with no significant effects on growth performance or carcass characteristics. However, feeding the soybean oil diet increased serum immunoglobulin-G (IgG) compared with feeding tallow and tallow-soybean oil diets, and increased the concentration of α-linolenic acid (C18:3n-3) and docosahexanoic acid (DHA, C22:6n-3) in carcass rib muscle and backfat, and increased the concentration of eicosapentanoic acid (EPA, C20:5n-3) in backfat. These results are consistent with other studies showing that feeding soybean oil or other oil sources rich in linolenic acid increase DHS and EPA content of pork adipose tissues (Romans, et al., 1995). Linolenic acid serves as a precursor to EPA and DHA through de novo synthesis involving desaturation and elongation (Romans et al., 1995; Scollan et al., 2001; Azain, 2004). Long-chain n-3 fatty acids serve as an essential components of membrane phospholipids (Stubbs and Smith, 1984), play a role in reducing the risk of cardiovascular disease in humans (Sanderson et al., 2002; Kouba, 2003), and are involved in neural and retinal development (Alessandri et al., 1998). Therefore, because soybean oil contains relatively high concentrations of linolenic acid, its use in growing-finishing pig diets can be beneficial for producing pork in niche markets desiring pork products enriched with these n-3 fatty acids.

In addition, a few studies have shown that supplementing soybean oil in sow diets during gestation and lactation appear may have beneficial effects for improving offspring immune function, intestinal morphology and enzyme production. Peng et al. (2019) fed control corn-soybean meal-wheat bran diets, with or without 2% soybean oil, throughout gestation, and a common diet during lactation. Although they

observed no difference in sow and litter performance between dietary treatments, sows fed the soybean oil diet had increased plasma concentration of prolactin (one of the major hormones involved in initiation and maintenance of milk production) at farrowing, and greater protein and non-fat solids content of milk than sows fed the control diet. Furthermore, piglets from sows fed the soybean oil diets had improved intestinal morphology and increased abundance of innate immunity related genes compared to offspring from sows fed the control diets.

Similarly, Liu et al. (2016) fed a control or 4.6% soybean oil diet to sows during gestation and observed improvements in body weight, small intestinal weight, and villus height of fetuses and piglets. They also reported a marked increase in lactase activity in the fetal intestine, increased sucrase activity in the piglet intestine, and a trend for increased protein expression of insulin-like growth factor 1 receptor expression in the fetal intestine from sows fed the soybean oil diet. Che et al. (2016) also compared intestinal development and transcriptional profile of offspring from sows fed a control or 4.5% soybean oil diet during gestation. Feeding the soybean oil diet increased fetal weight and intestinal lactase activity, along with altering multiple genes associated with the immune system, signal transduction, and metabolism.

Azain (1993) conducted a study to determine the effects of feeding diets containing medium-chain triglycerides (MCT) and long-chain triglycerides (LCT; 2% soybean oil) during late gestation and early lactation on pre-weaning survival. Although sows fed the MCT supplemented diet resulted in greater survival (90.3%) until weaning at 21 days, greater number of pigs weaned per litter (10.1 pigs), and greater litter weaning weights (58.9 kg), compared with feeding LCT (81.2%, 8.9 pigs, and 48.5 kg, respectively), survival of low birth weight (< 900 g) pigs was improved by feeding sow diets containing either MCT (68%) or LCT (53%) compared with feeding the control diet (32%). This improvement in low birth weight piglet survival was partially attributed to the increase in total lipid content, and an increase in the polyunsaturated fatty acid to saturated fatty acid ratio in sows fed the LCT diet.

EFFECTS OF DIETARY SOYBEAN OIL ON RESPIRATORY HEALTH OF SWINE

Confinement swine facilities often have significant concentrations of dust and gases that can be detrimental to respiratory health of humans and pigs. Several studies have shown that when pigs are exposed to high concentrations of dust and gases, growth and feed efficiency is often reduced (Curtis et al., 1974; 1975; Wathes et al., 2004), along with reduced respiratory health (Doig and Willoughby, 1971; Bundy and Hazen, 1975; Drummond et al., 1981). Dust particles that are smaller than 5.2 μm in diameter are capable of penetrating the lungs of humans and pigs (Anderson, 1958), and can be carriers of viruses and bacteria (Roller, 1961; 1965; Carlson Whenham, 1967), which causes dust to be a health concern. Therefore, efforts to control dust in confinement swine facilities is essential to minimize the adverse health effects on pigs and people.

The addition of soybean oil to swine diets has been shown to be effective in reducing dust and associated bacteria and virus concentrations in confinement swine facilities. Mankell et al. (1995) reported that adding 1% soybean oil swine diets markedly reduced dust concentrations, and the addition of 3% soybean oil resulted in further reduction in dust. Gore et al. (1986) showed that the addition of 5% soybean oil to diets reduced dust concentrations by 45 to 47%, and total aerosol bacterial colony counts by 27% compared with feeding to diets with no supplemental soybean oil. Verreault et al. (2010) reported that concentrations of up to 107 genomes of porcine circovirus type 2 (PCV2) can be found per cubic meter of air in confinement facilities housing pigs infected with this virus, and that airborne dust concentrations were correlated with

airborne concentrations of PCV2 (r = 0.41) and total bacteria (r = 0.60). Therefore, using soybean oil to reduce dust levels in confinement swine facilities should be considered to minimize dust and subsequent pathogenic bacteria and virus inhalation that may have detrimental effects of animal health

SUMMARY

Although soybean oil is not often considered to have important health and immune system benefits for poultry and swine compared with lipid sources containing greater concentrations of n-3 fatty acids, there is some indication from the limited studies conducted that it has some beneficial effects. Soybean oil contains high concentrations of linoleic acid, which serves as a precursor for de novo synthesis of EPA and DHA through a conversion process involving desaturation and elongation. Although limited studies in poultry have shown inconsistent benefits for improving antibody titers against common diseases, studies in swine have shown an improvement in immune function, intestinal morphology and enzyme production of offspring of sows fed soybean oil. Furthermore, the addition of soybean oil to reduce dust levels in confinement swine facilities should be considered to minimize dust and subsequent pathogenic bacteria and virus inhalation that may have detrimental effects of animal health.

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Chapter

12

Effects of Feed Additives on Energy Utilization of U.S. Soybean Oil in Swine and Poultry Diets

INTRODUCTION

Once a high quality lipid source is selected for use, the goal is to maximize its feeding value in swine and poultry diets. There continues to be considerable interest in adding several types of feed additives, such as emulsifiers (lecithin, lysolecithin, bile salts), L-carnitine, and supplemental feed enzymes to diets containing supplemental fats and oils to enhance digestibility and metabolizable energy content. This chapter summarizes numerous studies that have been conducted to evaluate these various feed additives for improving energy digestibility and growth performance in poultry and swine fed soybean oil diets, with some references to other lipid sources for comparison.

Table 1. *Comparison of energy and nutrient content of soybean oil and feed grade soy lecithin (Anonimo, 2010)*

Measure	Soybean oil	Feed grade soy lecithin
Gross energy, kcal/kg DM	9,291	7,046
AME_n broilers, kcal/kg	9,232	6,998
Total fatty acids, % of lipid	95.3	71.5
Linoleic acid, %	51.0	38.3
Total phosphorus, %	0	3.94
Digestible phosphorus, %	0	3.55
Choline, %	0	3.94

EMULSIFIERS – LECITHIN AND LYSOLECITHIN

POULTRY DIETS

Nutritional emulsifiers (lecithin and lysolecithin) are classified based on their hydrophilic-lipophilic balance, which indicates its extent of solubility in water or fat, where 0 = very lipophilic and 20 = very hydrophilic. Therefore, an emulsifier with a high hydrophilic-lipophilic balance indicates high water solubility, and will be most effective in poultry diets because of the high proportion of water relative to dry feed consumed by birds.

Lecithins are naturally occurring compounds in soybeans, and are produced by hydrating raw soybean oil with steam to precipitate the lecithin gums. Several commercial sources of feed grade lecithins are available in most countries at a competitive price. Unprocessed lecithin gums contain about 25% moisture, 50% phospholipids, and 25% soybean oil (Russet, 2000), and are used in poultry diets as a substitute for other lipids, as well as an emulsifier to increase lipid digestibility in young birds. A comparison of the composition of the energy content (broilers) and selected nutrient concentrations in soybean oil and feed grade soy lecithin is shown in **Table 1.** The gross energy (GE) and nitrogen-corrected apparent metabolizable energy (AMEn) content of feed grade soy lecithin are both about 24% less than found in soybean oil. This is likely due to the lower total fatty acid content in lecithin compared with soybean oil. Borsatti et al. (2018) developed regression equations to estimate AMEn content of several soybean oil by-products, including lecithin.

Limited studies have evaluated the use of lecithin to improve lipid digestibility in broiler diets. Polin (1980) added 0.2, 2.0, or 20 g/kg lecithin to diets containing 4% tallow and reported an improvement in digestibility when the 20 g/kg dietary concentration was used, but not the lower concentrations. More recently, Siyal et al. (2017) reported that adding 0.10% soy lecithin to broiler diets con-

taining 4.2 to 5.5% palm oil improved growth performance, reduced serum cholesterol and triglycerides, and improved oxidative status. It is unknown if these same benefits occur when adding lecithin to broiler diets containing soybean oil.

Lecithin has also been evaluated for use in layer diets as a substitute for other lipid sources. Mandalawi et al. (2015) reported that replacing lard (pork fat) with 4% lecithin in layer diets improved retention of dry matter, lipid, and gross energy, as well as improved egg weight and egg yolk color.

Commercial lysolecithin products are mixtures of lysophospholipids (including lysophosphatidyl choline) and phospholipids. The relatively high hydrophilic-lipophilic balance in lysophospholipids compared with phospholipids allow them to serve as a very effective biosurfactants with the capability of more effectively forming small sized micelles than bile (Melegy et al., 2010).

Several studies have evaluated the addition of commercial sources of lysolecithin products on energy content and growth performance of broilers. Othman (2008) evaluated the addition of lysophosphatidylcholine to diets containing 4% tallow or soybean oil and observed an improvement in AME content and feed conversion during a 35-day feeding trial, for diets containing both lipid sources. Zhang et al. (2011) added lysophosphatidylcholine to diets containing soybean oil, tallow, or poultry fat (3% inclusion in starter diets; 4% inclusion in grower diets), and showed an improvement in body weight gain during the starter phase for all lipid supplemented diets when the emulsifier was added, but not during the grower phase. The addition of lysophosphatidylcholine to these lipid supplemented diets tended to improve AME content during both growth phases, but the greatest improvement was when the poultry fat supplemented diets were fed. Similarly, Jensen et al. (2015) showed improvements in AME content and nitrogen retention when adding soybean and rapeseed lysolecithins to diets containing soybean oil or lard, but greater improvements were observed when feeding the lard diet. While some nutritional and growth performance benefits have been observed when adding emulsifiers to soybean oil diets, it appears that there are greater benefits when supplementing these products in diets containing animal fat sources. Furthermore, Boontiam et al. (2019) showed that supplementing lysophospholipid to low energy, low crude protein diets for broilers improved dry matter, ether extract, and amino acid digestibility, which led to improved body weight gain and feed conversion.

SWINE DIETS

Kerr and Shurson (2017) provided a detailed comparison of the fatty acid profile, oxidation indicators, and energy values between refined soybean oil and soy lecithin for swine **(Table 2).** Although the fatty acid profile was similar between refined soybean oil and soy lecithin, the gross energy (GE), digestible energy (DE), and metabolizable energy (ME) values are 26, 34, and 30% less, respectively, for lecithin compared with soybean oil. The soy lecithin source evaluated by Kerr and Shurson (2017) was also more oxidized than the refined soybean oil source, which may have affected the DE and ME content.

Kerr and Shurson (2017) also compared the energy content and digestibility of refined soybean oil and soybean acid oil, with or without the addition of lecithin, in 13 kg pigs. Gross energy content was similar among oils, with or without lecithin, but the addition of lecithin to the refined soybean oil had no effect of DE, DE as a percentage of GE, lipid digestibility, ME, and ME as a percentage of DE **(Table 3).** However, the addition of lecithin to soybean acid oil reduced DE, DE as a percentage of GE and ME content. It was expected that the addition of lecithin to the refined soybean oil would improve DE and ME content and

Table 2. *Comparison of composition and oxidization indicators of refined soybean oil and soy lecithin on energy content for growing pigs (adapted from Kerr and Shurson, 2017)*

Measure	Refined Soybean Oil	Soy Lecithin
Ether extract, %	99.8	63.2
Free fatty acids, %	0.02	6.30
Fatty acid, % of total lipid		
Valeric (C5;0)	ND	ND
Caprylic (C8:0)	ND	0.35
Perlagonic (C9:0)	ND	ND
Capric (C10:0)	ND	0.26
Lauric (C12:0)	ND	0.57
Myristic (C14:0)	0.07	0.32
Pentadecanoic (C16:0)	10.3	ND
Palmitic (C18:0)	4.64	21.8
Palmitoleic (cis-9 C16:1)	0.08	0.12
Margaric (C17:0)	0.09	ND
Margaroleic (C17:1)0.06	ND	ND
Stearic (C18:0)	4.64	3.67
Oleic (cis-9 C18:1)	24.1	17.4
Linoleic (18:2n-6)	52.8	50.2
Linolenic (18:3n-3)	6.52	4.37
Nonadecenoic (C19:1)	0.23	ND
Arachidic (C20:0)	0.35	0.18
Gadoleic (C20:1)	0.19	ND
Behenoic (C22:0)	0.35	0.41
Lignoceric (C24:0)	0.13	0.30
Other fatty acids	0.14	0.19
MIU[2], %	4.05	4.86
Peroxide value, meq/kg	2.30	8.61
Anisidine value[3]	7.6	56
Hexanal, µg/g	1.72	13.5
GE, kcal/kg	9,398	6,922
DE, kcal/kg	8,315	5,511
ME, kcal/kg	8,368	5,840

[1]**ND = not detectable.**
[2]**MIU = sum of moisture, insolubles, unsaponifiable matter.**
[3]**There are no units for anisidine value.**

digestibility, but this did not occur, and lecithin supplementation was actually detrimental to energy content when added to soybean acid oil. However, several other research studies have shown that lecithin has minimal to no effects on lipid and energy digestibility, as well as growth performance in pigs (Overland et al., 1993a; 1993b; 1994; Miller et al., 1994; de Souza et al., 1995).

Limited studies have been conducted to evaluate the potential benefits of adding lysolecithin to lipid supplemented diets for swine. One of the initial studies showed that supplementation of lysolecithin to swine diets improved lipid digestibility, but had minimal effects on improving growth performance (Jones et al., 1992). However, responses from adding lysolecithin to lipid diets appear to be age dependent (Xing et al. 2004). This is supported by results reported by Gatlin et al. (2005), where lysolecthin had no effect on digestibility of partially hydrogenated choice white grease fed to finishing pigs.

Shi et al. (2019) fed diets containing 0% to 3% soybean oil or soybean lecithin to lactating sows immunoglobulin from soy lecithin in lactating sows and showed an improvement in weaning weight and growth rate of piglets from sows fed the 3% soy lecithin diet. Furthermore, serum and milk immunoglobulin concentrations increased by feeding 2% or 3% soy lecithin diets in sows and piglets. This is the first evidence suggesting potential beneficial effects of feeding soy lecithin to sows. However, the addition of emulsifiers, such as lecithin and lysolecithin, to diets supplemented with various lipids have resulted inconsistent benefits for improving lipid and energy digestibility in growing pigs (Jones et al., 1992; Overland et al., 1993a, 1993b; 1994; Gatlin et al., 2005).

BILE SALTS

POULTRY

Lipid digestion is a complex process that involves having an adequate amount of bile salts, which serve as emulsifiers, and the enzyme lipase, to maximize absorption and utilization of lipids. Bile

Table 3. *Energy content and digestibility of refined soybean oil and soybean acid oil, with or without the addition of lecithin, in 13 kg pigs (adapted from Kerr and Shurson, 2017)*

Measure, %	Refined soybean oil	Refined soybean oil + lecithin	Soybean acid oil	Soybean acid oil + lecithin
GE, kcal/kg	9,398	9,250	9,326	9,182
DE, kcal/kg	8,315[a]	8,934[a]	8,448[a]	7,280[b]
DE, % of GE	88.5[a]	96.6[a]	90.6[a]	79.3[b]
Ether extract digestibility, %	95.7	97.5	88.4	87.6
ME, kcal/kg	8,368[a]	8,975[a]	8,472[a]	7,418[b]
ME, % of DE	100.6	100.6	100.3	102.1

salts are essential components of the lipid digestion process because they reduce the surface tension between the oil and water interface to allow emulsification, and activate pancreatic lipase, and also prevent this enzyme from becoming denatured when it leaves the surface of emulsified fat droplets (Ravindran et al., 2016). There is some evidence suggesting that there is insufficient bile secretion in young birds, which results in low digestibility of lipids (Krogdahl, 1985; Tancharoenrat et al., 2013). Furthermore, young chicks have less ability to reabsorb bile salts than older birds, which likely influences their ability to optimize lipid digestibility at this stage of life (Serafin and Nesheim, 1967; 1970).

All studies that have evaluated the supplementation of bile salts in broiler diets have involved diets containing supplemental tallow (Fedde et al., 1960; Gomez and Polin, 1976; Polin et al., 1980; Kussaibati et al., 1982; Noy and Sklan, 1995; Alzawqari et al., 2011). The majority of these studies showed consistent results for improving lipid digestibility and growth performance when various bile salts were supplemented in tallow diets. However, it is unknown if these positive responses would be observed when feeding diets supplemented with soybean oil to broilers. In addition, it is important to recognize that the extent of improved lipid digestibility will likely vary depending on the specific bile salt added, and bile salts are currently too expensive to be used in practical poultry diets.

L-CARNITINE

The mitochondria is the major site of fatty acid oxidation in animal cells, and L-carnitine is required for the transport of long-chain fatty acids from the cytosol of the cell to the mitochondria for β-oxidation. The β-oxidation process involves lipid combustion (Carter et al., 1995) and energy production (Keralapurath et al., 2010). Therefore, reductions in carnitine concentration, or changes in metabolisms may lead to reduced energy production in the mitochondria (Arslan, 2006). As a result, dietary supplementation of L-carnitine may be beneficial for improving fatty acid oxidation and energy production to facilitate improved growth performance of pigs and poultry fed supplemental lipid diets.

POULTRY

The addition of supplemental L-carnitine to broiler diets has been shown to promote growth, enhance the immune system, provide antioxidant effects, and improve semen quality in poultry (Adabi et al., 2011). Some evidence suggests that the L-carnitine requirement may be increased under conditions of high growth rates, increased stress, and when feeding diets containing limited or no animal protein sources (Adabi et al., 2011). However, responses have been inconsistent. A few studies have shown that adding L-carnitine to lipid diets improved body weight gain and reduced abdominal fat content in broilers (Rabie et al., 1997a,b), but other studies found no effect of L-carnitine supplementation on growth performance (Xu et al., 2003; Leibetseder, 1995). These conflicting results may be due to differences in fatty acid composition among lipid sources being fed.

More recently, Jalali et al. (2015) evaluated the effects of feeding diets containing soybean oil or sunflower oil (3.85 starter; 5.4% grower), with and without 120 mg/kg of L-carnitine supplementation, on growth performance, blood chemistry measures, and antibody titer against Newcastle disease in broilers during a 5-week feeding trial. Broilers fed diets containing soybean oil had similar (main effects) daily body weight gain (61.7 g/day) compared with birds fed sunflower oil (57.8 g/day), but feed conversion was improved by feeding soybean oil (1.96) compared with feeding sunflower oil (2.09). However, there were no main effect differences among treatments for L-carnitine supplementation. When the interactive effects of oil source, with and without L-carnitine supplementation were compared, the addition of L-carnitine

to the soybean oil diets had a significant advantage **(Table 4).** For the overall 35-day feeding period, birds fed the soybean oil diets supplemented with 120 mg/kg L-carnitine had greater body weight compared to birds fed soybean oil without L-carnitine supplementation, and sunflower oil diets with or without L-carnitine supplementation. Body weight gain was improved for broilers fed the soybean oil and L-carnitine diets compared with feeding the unsupplemented soybean oil and sunflower oil with L-carnitine diets. Furthermore, feed conversion was greater for broilers fed the soybean oil and L-carnitine diets compared with birds fed the sunflower oil and L-carnitine diets. These results suggest that the addition of L-carnitine to broiler diets containing soybean oil can be effective in improving growth performance, but these benefits were not observed when adding L-carnitine to sunflower oil diets.

Sayed et al. (2001) reported increased feed intake of broilers fed 2 or 4% sunflower oil supplemented with 50 mg/kg of L-carnitine. In addition, Corduk and Sarica (2008) reported that adding 500 mg/kg of L-carnitine to laying hen diets containing sunflower oil increased feed intake in laying hens. However, other studies have shown that the addition of L-carnitine (300, 600, or 900 mg/kg) to corn oil supplemented broiler diets reduced feed intake (Zhang et al., 2010), and Ardekani et al. (2012) reported that adding 50 mg/kg of L-carnitine diets containing soybean oil reduced feed intake of broilers. Several other studies have shown no effect of supplemental L-carnitine on growth performance of broilers (Corduk et al., 2007; Lien and Horng, 2001; Xu et al., 2003; Kheiri et al., 2011).

Interestingly, the addition of supplemental L-carnitine to soybean oil diets has been shown to improve the antibody titer against Newcastle Disease virus (Jalali et al., 2015). In turkeys, the antibody titer against Newcastle Disease increased when the dietary ratio of n-3 to n-6 fatty acids was about 0.13, which is comparable to the ratio found in soybean oil (Friedman and Sklan, 1997). Pilevar et al. (2011) also reported that as the dietary n-6 to n-3 ratio increased, the antibody titer for Newcastle Disease also increased in pullet chicks. Therefore, there appear to be some additional benefits of adding L-carnitine to soybean oil diets for improving immune response against Newcastle disease, which were not observed when adding it to sunflower oil diets.

Table 4. *Interactive effects of feeding diets containing soybean oil, sunflower oil, or a combination of these oils, with and without L-carnitine supplementation, on growth performance, fat pad (% of 35 day body weight), and antibody titer against Newcastle disease virus (adapted from Jalali et al., 2015).*

Measure	Soybean oil	Soybean oil + L-carnitine	Sunflower oil	Sunflower oil + L-carnitine
Body weight at 35 days, g	2,294^{c}	2,693^{a}	2,493^{b}	2,308^{c}
Body weight gain, g/d	56.5b^{c}	66.8^{a}	62.2^{ab}	53.4^{c}
Feed intake, g/d	118	124	120	120
Feed:Gain	2.08^{ab}	1.85^{b}	1.93^{bc}	2.24^{a}
Fat pad, % of 35 day body weight	2.38^{b}	2.78^{a}	2.07^{bc}	1.75^{d}
Antibody titer against Newcastle disease virus at 28 days of age, Log_2	2.75^{b}	4.10^{a}	3.30^{ab}	3.70^{ab}

^{a,b,c,d}**Means within rows with uncommon superscripts are different (P < 0.05).**

SWINE

The addition of L-carnitine to diets containing supplemental lipids has been shown to improve energy content of lipid as a result of increased fatty acid oxidation in newborn pigs (Odle, 1997; Heo et al., 2002). This response may be a result of low dietary carnitine concentrations provided at weaning. Sow milk contains abundant quantities of carnitine (Kerner et al., 1984), and when pigs are weaned, this source of carnitine is no longer available and may require supplemental L-carnitine in their diets until they are capable of synthesizing adequate amount of carnitine.

Results from feeding diets containing supplemental L-carnitine have shown relatively consistent benefits for improved growth performance and energy and nutrient utilization. Cho et al. (1999) added 1,000 mg/kg of L-carnitine to weaned pig diets containing 4% soybean oil and increasing lysine levels, and showed improvements in GE, lipid, crude protein, and dry matter digestibility, as well as improvements in feed conversion. In contrast, Hoffman et al. (1993) fed diets containing 1.18% or 12.31% soybean oil, with or without 800 mg/kg of L-carnitine to weaned pigs and reported that L-carnitine had no effect on improving ME content of diets containing soybean oil, and that calories from soybean oil were used as efficiently as calories from carbohydrate by neonatal and young pigs. However, Owen et al. (1996) fed diets containing 0% or 10% soybean oil supplemented with 0, 500, or 1,000 mg/k of L-carnitine and observed an improvement in feed conversion and a reduction in carcass lipid accretion. In a subsequent study, Rincker et al. (2003) conducted five experiments involving the addition of 0% or 4% to 6% soybean oil to nursery pig diets supplemented with increasing diet concentrations of L-carnitine (0, 25, 50, or 100 mg/kg). They reported that the addition of 50 to 100 mg/kg L-carnitine to the diets improved growth performance, and this response was greater when soybean oil was added to the diet.

In growing pigs, Heo et al. (2000) evaluated the effects of supplementing 4% soybean oil, low energy diets with 500 mg/kg of L-carnitine on nitrogen utilization in 18 kg pigs and observed an improvement in growth rate, nitrogen digestibility and retention, and protein accretion, while lipid deposition in adipose tissue was reduced. Owen et al. (2001) fed nursery diets containing 3 to 5% soybean oil, and grower-finisher diets containing 2.5% soybean oil, which were supplemented with increasing levels of L-carnitine, and showed no effects of L-carnitine supplementation on growth performance during the nursery or grower-finisher periods. However, feeding diets containing 49 to 64 mg/kg of L-carnitine during the grower-finisher phase increased protein accretion and decreased backfat thickness of grower-finisher pigs.

An initial study with sows, showed that supplementing diets with L-carnitine in gestation, lactation, or both reproductive phases, increased subsequent number of pigs born alive per litter, while feeding diets supplemented with L-carnitine during gestation only increased litter weights at birth and weaning (Musser et al., 1999). However, in a review conducted by Eder (2009), although inconsistent responses from L-carnitine supplementation during gestation have been reported for litter size, most studies have shown improvements in piglet and litter weights at birth as well as improved growth rate during the nursing period. Studies evaluating the effects of L-carnitine supplementation in sow diets containing soybean oil are needed.

SUPPLEMENTAL FEED ENZYMES

POULTRY

Lipases are enzymes responsible for the digestion of dietary fats and oils. Some researchers have speculated that the amount of lipase produced from the pancreas in birds may be inadequate to optimize lipid digestion. Limited studies have been conducted to evaluate supplementing diets containing supplemental lipases in poultry diets. Two sources of lipases have been evaluated in poultry diets, which include crude porcine lipase (Polin et al., 1980) and lipases from microorganisms such as Rhizopus arrhizus, Aspergillus niger, and Pseudomonas spp. (Kermanshahi et al., 1988). Polin et al. (1980) fed diets containing 4% tallow which were supplemented with 0%, 0.1%, or 1% crude porcine lipase and 0% or 0.4% cholic acid to broilers. Fat digestibility improved during the first 9 days post-hatch in birds fed the diet containing 1% lipase, compared to birds fed the lower lipase supplementation levels, but adding only cholic acid resulted in greater fat digestibility (82.6%) compared with diets containing both 1% lipase and cholic acid (82.3%).

However, DiMango et al. (1977) reported that dietary porcine lipase is denatured by the low pH in the upper gastrointestinal tract of birds, and it loses much of its activity by the time it reaches the intestinal sites of lipid digestion. In a recent study, Hu et al. (2018) evaluated the effects of feeding diets containing different energy and lipase concentrations on growth performance, nutrient digestibility, serum profiles, gut health, and carcass quality in broilers. Tallow was used as the supplemental fat source in the experimental diets. Results showed that supplementing 3,000 units/kg of feed with lipase improved nutrient digestibility, growth performance, intestinal villus height, villus height:crypt depth, and lipase activity, but reduced serum triglyceride and low-density lipoprotein cholesterol concentrations, as well as percentage of abdominal fat when broilers were fed a reduced energy diet. It is unknown whether these benefits can be achieved when feeding diets containing soybean oil.

A series of 3 experiments were conducted by Al-Marzooqi and Leeson (1999) to evaluate the addition of pancreatin and a crude porcine pancreatic preparation on lipid utilization in diets for young broilers. In the first experiment, supplementing diets containing 4% or 8% of an animal-vegetable blend source 7.14% crude pancreatic enzyme or 7.14% pancreatin, improve lipid digestibility and AME content compared with feeding the unsupplemented diets. However, feeding diets with the supplemental enzymes resulted in reduced feed intake, body weight gain, and feed conversion compared with birds fed the control diets. Similarly, in the second experiment, increasing diet concentrations of the crude pancreatic enzyme (0, 2.14, 4.29, 6.43, 8.57, and 10.71%) in diets containing 4% of an animal-vegetable blend increased fat digestibility and AME content, but reduced feed intake, body weight gain, and feed conversion. In the third experiment, broilers were fed a 4% animal-vegetable blend diet containing increasing concentrations of dried crude porcine pancreas, but no effects on growth performance were observed. These results suggest that while supplementation of pancreatin may improve lipid digestibility, these improvements do not subsequently result in improvements in growth performance.

Meng et al. (2004) fed a purified form of supplemental lipase to young broilers and observed no effect on lipid digestibility or AME. These researchers suggested that pancreatic lipase production may not be a limiting factor contributing to reduced lipid digestion in young birds.

The addition of various carbohydrases, proteases, and enzyme mixtures to poultry diets hae become very popular in recent years in an attempt to increase energy and nutrient digestibility in poultry diets containing sources of dietary fiber. Poultry diets comprised of cereal grains, contain fiber which causes increased digesta viscosity and reduces lipid digestibility (Ward and Marquardt, 1983; Choct and Annison, 1992). As a result, high fiber cereal based diets are commonly supplemented with xylanases (carbohydrases) to minimize the detrimental effects caused by viscosity, and improve energy and nutrient digestion and growth performance in broilers.

Dänicke et al. (1997) fed rye-based diets containing 10% soybean oil or tallow, with or without a supplemental xylanase enzyme to broilers. They observed greater feed intake and body weight gain when broilers were fed the soybean oil diets compared with feeding the tallow supplemented diets, and adding xylanase to the 10% tallow diets improved feed conversion to a similar level as birds fed the soybean oil diets without supplemental xylanase. This improvement was attributed to the reduction in viscosity of ileal digesta, which subsequently improved lipid digestibility and growth performance compared with birds fed the unsupplemented xylanase diets.

Langhout et al. (1997) fed wheat and rye-based diets containing 6.5% soybean oil or a blend of 6% tallow and 0.5% soybean oil, with or without xylanase supplementation. Similar to results reported by Dänicke et al. (1997), birds fed diets containing the tallow-soybean oil blend and xylanase resulted in a greater improvement in lipid digestibility than when xylanase was added to the soybean oil diets. These results suggest that xylanase supplementation in soybean oil diets fed to broilers has minimal effects on improving lipid digestibility than in diets containing animal fat sources.

SUMMARY

There has been considerable interest in using effective feed additives to improve lipid digestibility, and growth performance of pigs and poultry fed diets containing soybean oil and other lipids. Soy lecithin can serve as both an energy source and emulsifier, but its energy content is substantially less than that of soybean oil and its effectiveness as an emulsifier for improving digestibility is minimal in swine diets and questionable in poultry diets. Furthermore, the addition of commercially available lysolecithin products appear to have minimal benefits for improving digestibility and AME content of soybean oil supplemented diets for poultry, and greater benefits when added to diets containing animal fats. The addition of L-carnitine to soybean oil supplemented diets has resulted in inconsistent responses in broilers, but recent evidence suggests that it may improve antibody titers against Newcastle Disease virus while also improving body weight gain and feed conversion compared to feeding unsupplemented soybean oil or sunflower oil diets, with or without L-carnitine supplementation. Several studies have shown improvements in lipid and energy digestibility when L-carnitine is supplemented in soybean oil diets for nursery pigs, and improvements in carcass lean deposition and reduction in backfat when feeding diets containing soybean oil and L-carnitine fed to growing-finishing pigs. Similarly, supplementing sow diets with L-carnitine has shown consistent benefits for improving reproductive performance, but no studies have evaluated its supplementation in sow diets containing soybean oil. Use of bile salts as supplements to poultry diets appear to provide benefits for improving lipid digestibility and AME content in diets supplemented with tallow, but it is unknown if these effects would also be observed in diets containing soybean oil. Regardless, the supplementation of bile salts in swine and poultry diets is currently cost-prohibitive. Lastly, the addition of xylanases in cereal grain-based diets containing supplemental soybean oil appear to be effective in reducing viscosity and improving lipid digestibility, but little is known about these potential benefits in pig diets.

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Chapter

13

Energy Value of Soybean Acid Oil in Swine and Poultry Diets

INTRODUCTION

Acidulated or "acid" vegetable oils, including soybean acid oil, are by-products of the oil refining process. As crude soybean oil undergoes the refining process and alkaline neutralization, about 6% of the total volume is separated as soybean oil soapstock. The composition varies depending on soybean seed quality, as well as oil extraction and refining conditions, but it is comprised of a mixture of neutral oil, water, free fatty acids, phospholipids, unsaponifiable matter, proteins, and mucilaginous compounds (Hammond, 2005). This unstable by-product is further processed by treating with sulfuric acid in a hot aqueous solution to produce acidulated soybean oil soapstock (Hammond, 2005). Acid soybean oil contain relatively high concentrations of free fatty acids (> 50%), unsaponifiable matter, oxidized fatty acids, and carotenoids, with a pH of 2.5 to 3.0 (Bornstein and Lipstein, 1963: Lipstein et al., 1965; Pardio et al., 2001). The majority of soybean acid oil is used as an animal feed ingredient, but some is also used in soap manufacturing and foundries. Soybean acid oil is considered to be the least valuable by-product of soybean oil processing, and is commonly priced at a significant discount to crude degummed soybean oil (Hammond, 2005).

High quality acid oils must be stabilized with antioxidants because they typically contain 40 to 55% free fatty acids, and may be as high as 90 to 98% free fatty acids (Kerr and Shurson, 2017). In general, fats and oils containing high concentrations of free fatty acids have lower energy value because there is an insufficient quantity of monoglycerides to combine with the high proportion of free fatty acids resulting in impaired reduced lipid absorption (Blanch et al., 1995). However, this does not appear to be true for soybean acid oil because of lower concentrations of glycerin in acid oil, which has less energy value than fatty acids, and does not dilute the metabolizable energy (ME) content. Although the high concentration of free fatty acids in acidulated soybean oil is the most important distinguishing characteristic compared to crude soybean oil, it can have 95 to 100% the ME value of degummed soybean oil for swine (Kerr and Shurson, 2017). Furthermore, unlike degummed soybean oil, the high free fatty acid content in soybean acid oil is not a good indicator of oxidation, as it is for non-acidulated fats and oils, but antioxidants must be added to decrease oxidation and stabilize acidulated fats and oils.

ACIDULATED SOYBEAN OIL FOR SWINE

A recent study by Kerr and Shurson (2017) evaluated the fatty acid composition, oxidative status, and energy value of various commercially available specialty lipids including an animal-based fat source containing a high percentage of C16:0 and C18:0 fatty acids, an animal-based fat source containing a high percentage of C16:0 and C18:0 free fatty acids (FFA), refined U.S. soybean oil, and a high FFA soybean acid oil for growing pigs. The fatty acid profile of the high FFA soybean oil source was modified during the manufacturing process resulting in a loss of oleic, linoleic, and linolenic acids, which corresponded to an increase in steric, palmitic, myristic, and lauric acids compared with those in refined soybean oil **(Table1).** There were minor differences in moisture, insolubles, and unsaponifiables (MIU) content among these lipid sources, but soybean acid oil source had greater peroxide value, anisidine, and hexanal values compared to the other lipid sources, which was likely a result of the greater susceptibility to oxidation during the manufacturing process. Although these animal fat and soybean oil sources contained similar gross energy (GE) content, when they were acidulated (increase FFA content), the digestible energy (DE) and ME content of animal fat was substantially reduced while the DE and ME content of soybean acid oil was comparable to refined soybean oil for pigs **(Table 1).** Considering only the unsaturated to saturated fatty acid ratio (U:S) when evaluating relatively energy values among lipid sources can be misleading. For example, coconut and palm kernel oils contain high concentrations of saturated fatty acids (about

77%), but are highly digestible and have relatively high ME content because the majority of fatty acids in these sources have chain lengths less than 14 carbons (NRC, 2012). However, the U:S is an important consideration for lipids containing high concentrations of fatty acids with more than 16 carbons. Therefore, feeding acid oils with a high FFA content is not a problem as long as they consist of shorter chain fatty acids (C14:0, C16:0, C18:0), are present in relatively low concentrations, and contain relatively high concentrations of long-chain unsaturated fatty acids (such as in soybean acid oil). Kerr and Shurson (2017) showed that although animal fat and soybean oil contain similar GE content, when these fat and oil sources are acidulated (increased FFA content), the DE and ME content of animal fat is substantially reduced while the DE and ME content of soybean acid oil is comparable to refined soybean oil for pigs **(Table 1).** Acidulated oils typically contain about 50% of the glycerin content found in crude soybean oil. Because glycerin contains much less energy value than free fatty acids, the greater free fatty acid content in soybean acid oil generally results in a high DE and ME content for pigs and poultry.

Table 1. *Comparison of composition and oxidization indicators of fats and oils with and without acidulation on energy content for growing pigs (adapted from Kerr and Shurson, 2017)*

Measure	High C16;0 and C18:0 Animal Fat	High FFA Animal Fat	Refined Soybean Oil	High FFA Soybean Oil
Ether extract, %	96.9	99.7	99.8	99.9
Free fatty acids, %	2.80	98.1	0.02	89.6
Fatty acid, % of total lipid				
Valeric (C5;0)	ND[1]	0.29	ND	ND
Caprylic (C8:0)	ND	0.39	ND	0.45
Perlagonic (C9:0)	ND	0.80	ND	ND
Capric (C10:0)	ND	0.16	ND	0.39
Lauric (C12:0)	0.70	0.26	ND	3.08
Myristic (C14:0)	3.55	3.84	0.07	1.75
Pentadecanoic (C16:0)	26.7	37.8	10.3	16.3
Palmitic (C18:0)	55.3	41.2	4.64	3.55
Palmitoleic (cis-9 C16:1)	0.16	0.33	0.08	ND
Margaric (C17:0)	2.11	1.87	0.09	ND
Margaroleic (C17:1)0.06	0.06	0.06	ND	ND
Stearic (C18:0)	55.3	41.2	4.64	3.55
Oleic (cis-9 C18:1)	9.18	8.60	24.11	22.23
Linoleic (18:2n-6)	0.11	1.01	52.84	45.51
Linolenic (18:3n-3)	0.21	0.18	6.52	4.97
Nonadecenoic (C19:1)	ND	ND	0.23	ND
Arachidic (C20:0)	0.61	0.57	0.35	ND
Gadoleic (C20:1)	ND	ND	0.19	ND
Behenoic (C22:0)	ND	ND	0.35	0.67
Lignoceric (C24:0)	ND	ND	0.13	0.72
Other fatty acids	1.37	2.12	0.14	ND
MIU[2], %	0.79	2.02	4.05	8.13
Peroxide value, meq/kg	7.57	5.83	2.30	23.9
Anisidine value[3]	0.40	17.9	7.6	173
Hexanal, µg/g	1.21	3.27	1.72	13.5
GE, kcal/kg	9,397	9,142	9,398	9,326
DE, kcal/kg	3,110	4,612	8,315	8,448
ME, kcal/kg	3,108	4,862	8,368	8,472

[1]ND = not detectable.
[2]MIU = sum of moisture, insolubles, unsaponifiable matter.
[3]There are no units for anisidine value.

Mendoza and van Heugten (2014) determined the apparent total tract digestibility of oil and GE content, as well as growth performance responses in weaned pigs fed 6% soybean oil (0.3% FFA) and

Table 2. *Chemical and physical quality specifications of degummed and acid soybean oils (Compêndio Brasileiro de Alimentação Animal, 2000)*

Measure	Degummed soybean oil	Acid soybean oil
Maximum moisture, %	0.50	1.0
Minimum total fatty acids, %	98	30
Maximum unsaponifiable matter, %	1.5	2.0
Saponification value, %	195-198	195-198
Iodine value, g/110 g	125-135	115-125
Maximum peroxide value, mEq/1000 g	3.0	-
Total acidity, %	3.0	-
Density, g/mL	0.93	0.93
Color	amber	dark brown

a soybean-cottonseed acid oil blend (70.5% FFA). Initial peroxide value (1.8 mEq/kg oil) and anisidine value (5.8) were less in the soybean acid oil blend than in soybean oil (33.6 and 12.4, respectively). They concluded that feeding diets containing acidulated lipids resulted in similar growth performance compared with refined lipids and could serve as economical alternatives to more expensive lipid sources.

ACIDULATED SOYBEAN OIL FOR POULTRY

A comparison of chemical and physical quality specifications of crude degummed soybean oil and acid soybean oil is shown in **Table 2.** Note that soybean acid oil contains a substantially lower total fatty acid content than degummed soybean oil, slightly greater moisture and unsaponifiable matter content, with similar iodine value and bulk density, but a darker color.

Wiseman and Salvador (1991) evaluated the ME content of tallow, soybean oil, and palm oil, as well as their respective acidulated forms with different concentrations of FFAs in broiler diets. They observed the reduction in ME content of fats and oils was greater with increasing concentrations of free fatty acids, and this magnitude of reduction was increased as diet inclusion rates were increased. Furthermore, the magnitude of reduced ME content with increasing FFA content was greater in saturated lipid sources (e.g. tallow) than in unsaturated sources (e.g. soybean oil), and the effects were more pronounced in young birds compared with older birds.

A summary of published AME values for acid soybean oil for poultry are shown in Table 3. Freitas et al. (2002) suggested that the AMEn content of acidulated soybean oil soapstock was 7,788 and 8,610 kcal/kg for young and adult birds, respectively. Baião and Lara (2005) summarized a few studies (Butolo, 2002; Nascif et al., 2004; Lara, 2004) that reported energy values for acid soybean oil, crude degummed soybean oil, and various other lipid sources for poultry. For birds less than 3 weeks of age, the ME content of soybean acid oil was 7,800 kcal/kg, which increased to 8,100 kcal/kg for birds more than 3 weeks of age, which were less than the AME content of 8,790 kcal/kg for degummed soybean oil. Leeson and Summers (2001) also reported digestibility values for acid soybean oil and crude degummed soybean oil based on bird age. For birds 3 to 4 weeks of age oil digestibility was 88% for soybean acid oil compared with 96% for degummed soybean oil, but at > 8 weeks of age differences in digestibility narrowed to 93% for soybean acid oil compared to 96% digestibility for degummed soybean oil. Iran-

doust et al. (2012) determined that the AME content in acidulated soybean oil soapstocks with 67.4% free fatty acids was 7,954 kcal/kg for layers. The AME estimate (8,527 kcal/kg) determined by Veira et al. (2015) is comparable to the estimate of 8,610 kcal/kg determined by Freitas et al. (2002) for older birds. The most recent estimate of AMEn content of acidulated soybean soapstock was determined by Borsatti et al. (2018), who reported a value of 7,153 kcal/kg, and developed a regression equation using the slope of the regression based on AMEn intake relative to feed intake (Y = 7,153X - 451.9; r2 = 0.79). Similar to other sources of fats and oils, the AME content of soybean acid oil varies considerably (6,679 to 8,598 kcal/kg). This variability is partly attributed to age of the bird, diet inclusion rate, composition of basal diet, as well as the free fatty acid content and extent of oxidation in the various sources of soybean acid oils evaluated. Interestingly, Cascabulho (2000) reported that the concentrations of linoleic acid in broiler carcasses was less when feeding acidulated soybean oil soapstock compared with feeding diets containing refined or crude soybean oil.

Table 3. *Summary of estimated AME content of acidulated soybean oil for poultry from various publications.*

Criteria	AME, kcal/kg	Reference
Various ages	6,679	Vilà and Esteve-Garcia (1996)
25 days of age	8,349 – 8,598	Zumbado et al. (1999)
Young birds	7,788	Freitas et al. (2002)
Adult birds	8,610	Freitas et al. (2002)
3 weeks of age	7,488	Freitas et al. (2005)
Roosters	8,610	Freitas et al. (2005)
Birds < 3 weeks of age	7,800	Baião and Lara (2005)
Birds > 3 weeks of age	8,100	Baião and Lara (2005)
Layers	7,858 - 7,954	Irandoust et al. (2012)
5 weeks of age	8,527	Veira et al. (2015)
	6,715	Gaiotto et al. (2001)
4 weeks of age	7,951 – 9,232	Peña et al. (2014)
3 to 4 weeks of age	7,153	Borsatti et al. (2018)

However, when purchasing and feeding soybean acid oil, it is important to ensure that it has not been adulterated by the addition of other low quality oils (Vieira et al., 2002). Mateos et al. (2012) indicated that acidulated soapstocks (pH < 5.0 and low MIU content) are acceptable energy sources for use especially in broiler finisher and layer diets. However, Ravindran et al. (2016) suggested that when using acidulated lipid sources containing high concentrations of free fatty acids for poultry, 1) they may be fed in fat blends which should contain sufficient amounts of triglycerides to ensure optimal digestion, absorption and energy utilization, 2) the proportion of FFA must be controlled, and 3) the U:S ratio of the final blend must be considered.

Irandoust et al. (2012) compared hen and egg production performance when feeding diets containing 4% soybean oil (9,127 kcal/kg AMEn) or acidulated soybean oil soapstock (7,966 kcal/kg AMEn) during a 6-week production period. No differences were observed for feed intake, body weight gain, egg production rate, egg mass, and feed conversion between dietary treatments (Table 4).

Table 4. *Comparison of laying hen and egg production performance from 44 to 56 weeks of age fed diets containing 4% soybean oil or acidulated soybean oil soapstock (adapted from Irandoust et al., 2012)*

Measure	Soybean oil	Acidulated soybean oil
Feed intake, g/day	100.0	98.2
Body weight gain, g	185	196
Egg production rate, %	85.9	85.0
Egg weight, g	60.4	60.2
Egg mass, g/day	51.9	59.1
Feed conversion, kg/kg	1.93	1.93
Feed conversion, kg/dozen	1.40	1.39

SUMMARY

Soybean acid oil is a lower quality, lower price energy source than crude, degummed soybean oil for swine and poultry, but studies have shown that it has a ME value 90 to 100% of degummed soybean oil despite its high free fatty acid content. This appears to be due to relatively low concentrations of medium chain fatty acids (C14:0, C16:0, C18:0) and a high proportion long-chain unsaturated fatty acids. However, soybean acid oil is more susceptible to oxidation than degummed soybean oil, and should be stabilized using antioxidants to prevent further oxidation before feeding to pigs and poultry.

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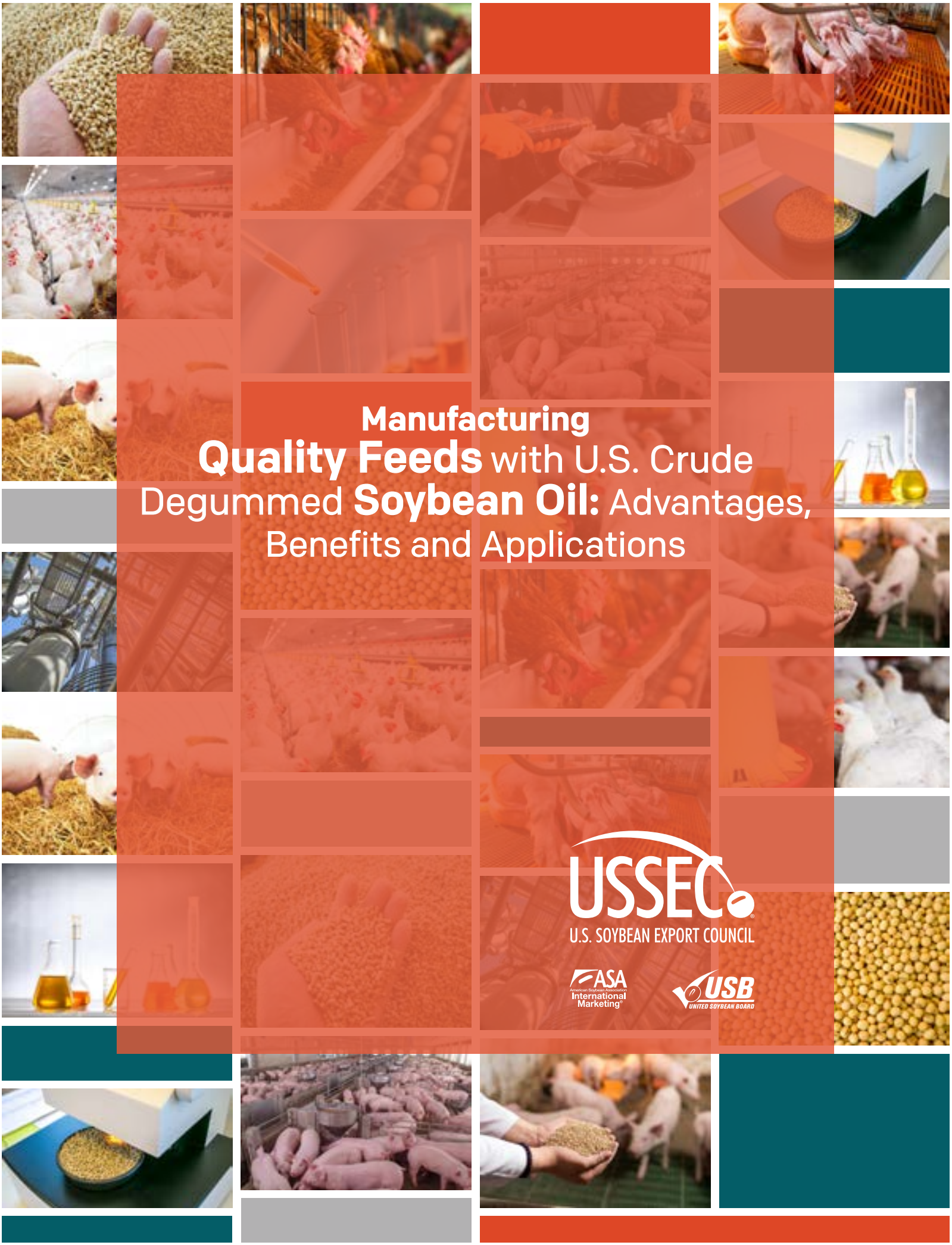

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