DIGESTIBILITY OF ENERGY AND NUTRIENTS IN DISTILLERS DRIED GRAINS WITH SOLUBLES FED TO GROWING PIGS

BY

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THESIS

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ABSTRACT

Distillers dried grains with solubles (DDGS) is a co-product of the ethanol industry. Composition and digestibility of nutrients can be influenced by the composition of the starting grains. In the United States, maize is the primary grain used to produce ethanol; however, in Europe and Canada, wheat is primarily used. Ethanol can also be produced from mixtures of grains, such as maize and wheat. Variability in nutrient composition and digestibility in DDGS can also be impacted by processing technologies that may or may not be implemented in the ethanol plant. Centrifugation of solubles is one such technology that may be implemented in ethanol plants to extract oil from solubles to be sold to the biodiesel industry. Two experiments are described in this thesis. The objective of the first experiment was to compare the standardized ileal digestibility (SID) of AA by growing pigs in European DDGS produced from wheat, maize, or wheat-maize mixtures. Twelve barrows (average initial BW: 23.0 ± 2.2 kg) were surgically equipped with a T-cannula in the distal ileum and randomly allotted to a replicated 6 × 6 Latin square design with 6 diets and 6 periods. The 5 sources of European DDGS that were used in the experiment included wheat DDGS from 2011, wheat DDGS from 2012, wheat-80 (80% wheat and 20% maize) DDGS, wheat-70 (70% wheat and 30% maize) DDGS, and maize DDGS. A diet containing each source of DDGS as the sole source of AA was formulated and an N-free diet was used to determine basal endogenous losses of CP and AA. Results indicated that the SID of AA in maize DDGS produced in Europe is greater than in European wheat DDGS and DDGS produced from mixtures of wheat and maize. The objective of the second experiment was to determine the DE and the ME in 23 sources of maize DDGS that were procured from ethanol plants in Illinois and surrounding states. Twenty-four barrows (average initial BW: 28.1 ± 1.8 kg) were randomly allotted to 1 of 24 dietary treatments in a 24 × 8 Youden square design with

24 diets and 8 periods. Twenty-four diets were formulated: 1 diet containing 97.8% maize and 23 diets containing maize and 40% of each source of DDGS. Each period consisted of a 7 d diet adaptation period and feces and urine were collected during the following 5 d based on the marker to marker approach. Results indicated that the nutrient composition, DE, ME, ATTD of GE, and ATTD of N in DDGS were different ($P < 0.05$) among sources. Prediction equations were generated to determine DE and ME in DDGS, however, the prediction equation were only moderately accurate ($R^2 \geq 0.74$).

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CHAPTER 1

INTRODUCTION

Ethanol is produced from yeast fermentation of starch-rich material, such as cereal grains (Liu, 2011). In North American, corn (maize) is the primary feedstock used for ethanol production (Stein and Shurson, 2009; Liu, 2011). However, in Europe and Canada, wheat is widely used (Nyachoti et al., 2005; Cozannet et al., 2010a; Rosenfelder et al., 2013). Mixtures of cereal grains are also being used (Stein and Shurson, 2009; Kiarie et al., 2013). Distillers dried grains with solubles (**DDGS**) is the main co-product of ethanol production. Compared with the starting feedstock, DDGS has a greater concentration of protein, fat, fiber, vitamins and minerals (Liu, 2011; Rosenfelder et al., 2013).

The feedstock used for ethanol production will influence the composition of DDGS. Wheat DDGS usually contains more CP and NDF, but less ether extract (**EE**), than corn DDGS, and variability in AA composition and digestibility among sources of wheat DDGS have been reported (Widyaratne and Zijlstra, 2008; Cozannet et al., 2010b; NRC, 2012). However, when corn and wheat are blended for ethanol production composition and digestibility of nutrients in the resulting DDGS may also vary (Widyaratne and Zijlstra, 2008; Kiarie et al., 2013)

There are several factors that influence the variability of nutrient composition and digestibility including grain variety, variation in composition of the starting feedstock, and ethanol processing procedures such as drying temperature and time, quality and amount of solubles added to the wet grains, and whether or not the ethanol plant is utilizing fractionation technologies (Shurson and Alghamdi, 2008; Liu, 2011). Conventional corn DDGS contains approximately 27% CP, 10% fat, 9% ADF, and 25% NDF (Stein and Shurson, 2009). Different processing technologies may result in production of DDGS with different concentrations of energy and nutrients (NRC, 2012). In the past few years, ethanol plants have been extracting oil via centrifugation of solubles to sell oil into the biodiesel industry (Rosentrater et al., 2012; Kerr et al., 2013). The resulting DDGS has decreased EE and possibly reduced concentrations of DE and ME.

Due to the variability caused by grain variety and the variability in fractionation technologies used for ethanol production it is important to determine nutrient composition and digestibility in DDGS sources. The objectives of this thesis are:

1. To compare the standardized ileal digestibility (**SID**) of AA by growing pigs in European DDGS produced from wheat, maize, or wheat-maize mixtures.
2. To determine if the concentration of DE and ME in DDGS produced in and around Illinois varies among plants.

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CHAPTER 2

DISTILLERS DRIED GRAINS WITH SOLUBLES FED TO PIGS: A LITERATURE REVIEW

INTRODUCTION

Distillers dried grains with solubles (**DDGS**) is a co-product of the ethanol industry. Federal tax exemptions were issued to increase the production of ethanol in order to reduce United States dependence on imported crude oil (Liu, 2011). The Energy Tax Act of 1978 (US Congress, 1978) stated that gasoline blended with at least 10% ethanol would be exempt from the federal fuel tax of 4 cents per gallon (Rosentrater, 2012). This was the first federal tax exemption for the inclusion of ethanol in gasoline and encouraged the production of ethanol. Federal fuel tax exemptions continued to be modified well into the 21st century, but it was not until 2005 that a standard for renewable fuels was established (Rosentrater, 2012). The Energy Policy Act of 2005 (US Congress, 2005) created the Renewable Fuels Standard (**RFS**) that describes the fuel volume mandate in the United States. In 2005, the RFS projected that the amount of renewable fuel produced in 2012 would be 7.5 billion gallons. When the RFS was revised in the Energy Independence and Security Act of 2007 (US Congress, 2007), it increased the applicable volume of renewable fuel of 2012 to 15.2 billion gallons and stated that by 2015, the fuel volume would increase to 20.5 billion gallons. In addition to the revised fuel volume, the RFS declared that corn ethanol would be produced to a maximum level of 15 billion gallons per year (Rosentrater, 2012; Mumm et al., 2014). This indicates that alternative fuel sources, i.e., cellulosic biofuel, biomass-based diesel, and advanced biofuels will have to increase to meet the projected fuel volume of 2015.

In response to government policy, ethanol production has risen from 1.3 billion gallons in 1993 to 13.3 billion gallons in 2013 (ERS, 2014; Renewable Fuels Association, 2014). In 2008, there was a total of 150 operating ethanol plants in the United States (Mueller, 2010), but as of January 2014, the total of operating ethanol plants has increased to 192 and these plants have the capacity to produce a total of 13,966 million gallons of ethanol per year (Renewable Fuels Association, 2014). In 2013, the United States ethanol production reduced dependency on imported oil from 41% to 35% by displacing 462 million barrels of imported oil (Renewable Fuels Association, 2014).

In the United States, corn is the main feedstock used for the production of ethanol (Cozannet et al., 2010a; Liu, 2011; Rosentrater, 2012). The total corn supply and price has increased from 8.9 billion bushels priced at $3.24 in market year 1995/96 to 11.9 billion bushels priced at $6.89 in market year 2012/13. (Figure 2.1; Figure 2.2; ERS, 2014). The amount of corn used for fuel ethanol production has increased from 396 million bushels in market year 1995/96 to 4.6 billion bushels in market year 2012/13. Approximately 39% of the total corn supply was used to produce ethanol in market year 2012/13 (ERS, 2014). The amount of corn used for feed or residual use has remained relatively stable over the last decade; however, from market year 2011/2012 to market year 2012/2013, the amount of corn used for feed or residual use decreased from 6.4 to 4.3 billion bushels (ERS, 2014). The decrease in corn used for feed or residual use may be due to the increasing price of corn or from producers incorporating other feed ingredients, i.e., DDGS, into diet formulations (Rosentrater, 2012).

PRODUCTION OF ETHANOL

Corn can be converted to ethanol via 3 different processes: wet milling, dry milling or dry grinding (Rausch and Belyea, 2006; Liu, 2011). At least 86% of corn ethanol is produced by the dry grind process (Mueller, 2010; Mumm et al., 2014) because they require less capital investment and less equipment compared with wet milling (Belyea et al., 2004). Therefore, the dry grind process will be the only process focused on in this review.

The major steps in production of ethanol from corn are receiving, milling, cooking, liquefaction, fermentation, saccharification, distillation, and storage (Figure 2.3; Rausch and Belyea, 2006; Han and Liu, 2010; Liu, 2011; Rosentrater et al., 2012). From storage, corn goes through a cleaning process, which can include sieves and magnets, to remove any broken kernels or foreign objects. After corn has passed the cleaning step, it is ground by either hammermills or roller mills to reduce the particle size and produce corn flour (Rausch and Belyea, 2006; Rosentrater et al., 2012). Before cooking, water and α-amylase are added to the corn flour, and this is now referred to as a slurry. The slurry is cooked inside a jet cooker at a temperature and pH between 120°C and 140°C and 5.5 and 6.0, respectively. The pH is adjusted by the addition of ammonia, lime, or sulfuric acid (Rosentrater et al., 2012). The purpose of cooking is to make starch more available for fermentation and also to decrease viscosity, which allows for better flow throughout the process (Winkler-Moser and Breyer, 2011; Rosentrater et al., 2012).

During fermentation and saccharification, glucose chains are broken down into dextrose by α-amylase and gluco-amylase. Temperature of the slurry is dropped from a range of 55°C to 65°C to 30°C in the fermentation tank that is held at a pH between 3.5 and 5.0 (Rosentrater et al., 2012). In the fermentation tank, yeast (*Saccharomyces cerevisiae*) and gluco-amylase are added to convert glucose to ethanol and to break down any remaining dextrins (Rausch and Belyea, 2006; Rosentrater et al., 2012). The resulting fermented liquid is known as beer and it travels through a beer well distillation system that has a stripping column to remove ethanol (Singh and Cheryan, 1998; Rausch and Belyea, 2006; Winkler-Moser and Breyer, 2011; Rosentrater et al., 2012). The column splits the beer into 2 streams: an overflow that consists of water and ethanol and an underflow that consists of whole stilage. The water and ethanol stream is further processed to remove water to produce ethanol.

CO-PRODUCTS OF ETHANOL PRODUCTION

The whole stilage can be centrifuged to produce thin stilage and wet grains (Rausch and Belyea, 2006; Rosentrater et al., 2012). At least 15% of thin stillage can be recycled back into the system, known as backset, to create the slurry of corn flour and water before cooking (Han and Liu, 2010; Liu, 2011). Whole stilage is processed to form a range of co-products.

Six different co-products result from the manipulation of whole stilage: condensed distillers solubles (**CDS**), dried solubles, distillers wet grains with solubles (**DWGS**), DDGS, distillers wet grains (**DWG**), and distillers dried grains (**DDG**). The CDS is recycled thin stillage that has passed through an evaporation system; if CDS is dried, the resulting product is dried solubles (Rosentrater et al., 2012). When whole stillage is centrifuged to produce wet grains and thin stillage, the wet grains can be sold as DWG or it can be dried to form DDG. The CDS can be mixed with the whole stillage to form DWGS and DWGS can be dried to form DDGS (Winkler-Moser and Breyer, 2011; Liu, 2011; Rosentrater et al., 2012). Benefits of producing dried products like DDGS include longer shelf life, due to low moisture content, and the product can be transported over longer distances; however, dried products use more electricity, which increases production cost because they require the use of a drier (Shurson and Alghamdi, 2008;

Rosentrater et al., 2012). Also, during the drying process of DDGS, the increase in temperature and presence of moisture and reducing sugars can result in Maillard reaction, which is known to reduce lysine concentration and digestibility (Pahm et al., 2008).

MODIFIED DISTILLERS DRIED GRAINS WITH SOLUBLES

Modifications, such as removing fractions of the feedstock that are not fermentable, have been made to the process of converting corn into ethanol to improve production efficiency (Liu, 2011). These modifications can be made either before or after fermentation, referred to as front-end and back-end fractionation, respectively (Shurson and Alghamdi, 2008; Winkler-Moser and Breyer, 2011; Rosentrater et al., 2012). By utilizing fractionation, it is possible to create new ethanol co-products and extract oil. Oil can be extracted by either front-end or back-end fractionation. (Shurson and Alghamdi, 2008; Winkler-Moser and Breyer, 2011; Rosentrater et al., 2012; US Grains Council, 2012).

Front-end fractionation is a fractionation of nutrients from the starting feedstock, in this case corn, versus back-end fractionation, which is a fractionation of nutrients from the co-product itself (Rosentrater et al., 2012; US Grains Council, 2012). Front-end fractionation separates corn into 3 components: endosperm (starch-rich), germ (oil-rich), and bran (fiber-rich). This allows for fermentation of only the starch-rich endosperm component for the production of ethanol. Oil can be extracted from the germ or the germ can be sold for livestock feeding (Shurson and Alghamdi, 2008; Rosentrater et al., 2012; US Grains Council, 2012). Corn germ, corn bran, and corn oil are the main co-products produced from front-end fractionation (Shurson and Alghamdi, 2008) and high-protein distillers dried grain (**HP-DDG**) is the co-product produced after fermentation of the endosperm (Widmer et al., 2007; NRC, 2012). HP-DDG contains greater crude protein, less fiber, and less fat compared with DDGS because most of the fiber fraction and fat is removed during the dehulling and degerming process, respectively (Widmer et al., 2007).

Back-end fractionation refers to removal of oil from the thin stillage. Thin stillage is first centrifuged to produce a low-fat thin stillage and oil (Winkler-Moser and Breyer, 2011), this low-fat thin stillage is then combined with whole stillage and the combined product is centrifuged to extract any remaining corn oil (Shurson and Alghamdi, 2008). This 2-step extraction procedure results in 40 to 70% of the fat in the thin stillage being removed. The remaining low-fat thin stillage is then added to the DDG resulting in the production of low-fat distillers dried grains with solubles (**DDGS-LF**). Oil that is removed during front-end fractionation is typically sold for human consumption, whereas oil extracted from whole stillage or thin stillage in back-end fractionation is typically used for livestock feed or biodiesel production (Winkler-Moser and Breyer, 2011).

Oil may also be extracted via centrifugation from CDS or from DDGS by solvent extraction using ethanol or hexane (Singh and Cheryan, 1998; Jacela et al., 2011; Moreau et al., 2010; Winkler-Moser and Breyer, 2011; Rosentrater et al., 2012; US Grains Council, 2012). When oil is extracted via back-end fermentation, the resulting DDGS has varying levels of fat. Conventional DDGS (**DDGS-CV**) contains greater than 10% fat, DDGS-LF contains 6 to 9% fat, and de-oiled DDGS (**DDGS-DO**) contains less than 5% fat (NRC, 2012). Removing oil via back-end fractionation increases the stability of the extracted oil because there is a greater amount of antioxidants in the oil compared with the corn germ oil produced in front-end fractionation (Winkler-Moser and Beyer, 2011). Creating a diverse profile of available corn co-products keeps the cost of DDGS high by decreasing the total amount available, allows for marketing of higher priced items, i.e. corn oil, and broadens the market of potential consumers (Singh et al., 2005; Shurson and Alghamdi, 2008; Moreau et al., 2010; Winkler-Moser and Beyer, 2011).

COMPOSITION OF DISTILLERS DRIED GRAINS WITH SOLUBLES

The composition of corn, wheat, corn DDGS, wheat DDGS, and DDGS derived from mixtures of corn and wheat is depicted in Table 2.1. The DDGS is typically composed of the non-fermentable material that remains after fermentation of the starting feedstock. Therefore, the concentration of protein, carbohydrate, and fat in DDGS is greater compared with the starting material (Liu, 2010).

Corn DDGS

Corn contains approximately 66% starch, 8% CP, 3% ADF, 11% NDF, and 4% acid hydrolyzed ether extract (**AEE**; NRC, 2012). When starch is removed during fermentation, the non-fermentable material becomes approximately 3 times as concentrated in DDGS compared with corn (Liu, 2011). The DM of DDGS is typically between 87 and 91% (Pedersen et al., 2007; Curry et al., 2014). On a DM basis, DDGS-CV usually contains 28 to 31% CP, 12 to 16% ADF, 31 to 40% NDF, 11 to 13% ether extract (**EE**), and 5,112 to 5,629 kcal/kg of GE (Spiehs et al., 2002; Pedersen et al., 2007, Stein et al., 2009; Anderson et al., 2012; Curry et al., 2014). However, DDGS-LF contains approximately 29 to 33% CP, 13 to 16% ADF, 34 to 42% NDF, 8 to 11% AEE, and 4,986 to 5,405 kcal/kg of GE (Spiehs et al., 2002; Pedersen et al., 2007; Stein et al., 2009; Anderson et al., 2012; Almeida et al., 2013; Kerr et al., 2013). Compared with DDGS-CV, DDGS-LF contains less EE, and therefore, the concentration of fiber and protein increases. De-oiled DDGS usually contains 31 to 35% CP, 15 to 18% ADF, 31 to 50% NDF, 4 to 5% EE, and 4,090 to 5,712 kcal/kg of GE (Jacela et al., 2011; Anderson et al., 2012; NRC, 2012;

Stein, 2012; Kerr et al., 2013). There is a greater concentration of protein and fiber as concentration of EE or AEE decreases in DDGS. Generally, the lower the concentration of EE or AEE is, the lower the GE is in DDGS.

Although DDGS has a greater concentration of protein compared with corn, the protein quality of DDGS can vary. During the production of DDGS, there are several heating steps, which can increase the opportunity for the Maillard reaction to occur, and therefore, reduce the concentration of lysine (Pahm et al., 2008). Stein (2007) recommends using DDGS with a Lys:CP ratio of at least 2.80%. The average Lys:CP ratio for DDGS-CV, DDGS-LF, and DDGS-DO are all above the recommended 2.80%; however, there are some DDGS sources that are heat damage as indicated by the SD in Table 2.1.

Wheat DDGS

Wheat contains approximately 60% starch, 11 to 14 % CP, 3% ADF, 11% NDF, and 2% EE (NRC, 2012). The DM (91 to 95%) in wheat DDGS is slightly greater than the DM (89%) in wheat (Emiola et al., 2009; Yang et al., 2010). Similar to corn DDGS, wheat DDGS is a concentrated form of the non-fermentable portion of the starting feedstock. Wheat DDGS contains 34 to 44% CP, 12 to 20% ADF, 30 to 47% NDF, 5% EE, and 4,349 to 5,079 kcal/kg of GE (Nyachoti et al., 2005; Widyaratne and Ziljstra, 2007; Lan et al., 2008; Cozannet et al., 2010a; Nitroyová et al., 2012). The SD of nutrient composition presented in Table 2.1 seem to be greater for the wheat DDGS compared with wheat, which indicates that there is greater variability in composition of wheat DDGS compared with the composition of wheat.

Corn DDGS vs. Wheat DDGS

Wheat contains greater concentrations of CP, ADF, and NDF compared with corn; however, corn contains more EE. Wheat DDGS has greater concentration of CP and ADF compared with corn DDGS, but wheat DDGS has similar concentrations of NDF as corn DDGS (Table 2.1). Wheat DDGS contains less EE compared with DDGS-CV and DDGS-LF, but EE in wheat DDGS is close to levels in DDGS-DO. The GE in wheat DDGS is less than in DDGS-CV, DDGS-LF, and DDGS-DO. It is expected that the GE in DDGS-CV and DDGS-LF is greater than wheat DDGS because of the greater concentration of EE in DDGS-CV and DDGS-LF. However, the DDGS-DO has greater GE than wheat DDGS, which is not expected because DDGS-DO has less EE compared with wheat DDGS. It is possible that the greater fiber fraction in DDGS-DO compared with wheat DDGS is contributing to the greater GE in DDGS-DO. Overall, there is greater variability in the composition of wheat DDGS compared with corn DDGS as indicated by the SD values in Table 2.1.

Wheat-corn DDGS

Ethanol can be produced from mixtures of different feedstocks, including mixtures of wheat and corn. The ratio of wheat:corn varies among plants. Composition of wheat-corn DDGS has been reported for wheat-corn ratios of 4:1, 7:3, and 1:1 (Widyaratne and Zijlstra, 2007; Yang et al., 2010; Azarfar et al., 2011; Ayoade et al., 2012); however, in some studies, the ratio of wheat:corn was not reported (Kiarie et al., 2013). The mean values for nutrient composition in wheat-corn DDGS is listed in Table 2.1. The DM in wheat-corn DDGS is typically between 90 and 94% (Azarfar et al., 2011; Kiarie et al., 2013). On a DM basis, wheat-corn DDGS contains 31 to 42% CP, 10 to 20% ADF, 32 to 47% NDF, 10% EE, and 5,112 to 5,293 kcal/kg of GE (Widyaratne and Zijlstra, 2007; Azarfar et al., 2011; Ayoade et al., 2012; Kiarie et al., 2013). In general, wheat-corn DDGS tends to have a nutrient composition that is intermediate between corn DDGS and wheat DDGS.

ENERGY VALUE OF DISTILLERS DRIED GRAINS WITH SOLUBLES

Corn DDGS

The DE in DDGS-CV is typically between 3,667 and 4,062 kcal/kg DM (Anderson et al., 2012; Kerr et al., 2013). The ME in DDGS-CV is usually between 3,465 and 3,875 kcal/kg DM (Pedersen et al., 2007; Kerr et al., 2013). The NE in DDGS-CV is approximately 2,437 kcal/kg DM (Gutierrez et al., 2014). The DE in DDGS-LF is typically between 3,631 and 4,252 kcal/kg DM (Stein et al., 2009; Kerr et al., 2013). The ME in DDGS-LF is between 3,419 and 3,976 kcal/kg DM (Stein et al., 2009; Kerr et al., 2013). The averages for DE and ME in DDGS-CV are similar to the DE and ME in DDGS-LF and both DDGS-CV and DDGS-LF have comparable DE and ME values that are comparable to corn (Table 2.1). However, the SD for DE and ME in DDGS-LF is greater than the SD for DE and ME in DDGS-CV, which indicates that there is greater variability of DE and ME in DDGS-LF compared with DDGS-CV. There is even greater variability of DE and ME in DDGS-DO, which is typically between 3,100 and 3,868 kcal/kg DM and 2,858 and 3,650 kcal/kg DM (Jacela et al., 2011; Anderson et al., 2012). The variability of DE and ME for DDGS-LF and DDGS-DO may be a result of the amount of oil that is removed during DDGS production, which impacts the amount of energy available.

Wheat DDGS

The DE in wheat DDGS is typically between 3,346 and 3,571 kcal/kg DM, the ME in wheat DDGS is usually between 3,143 and 3,339 kcal/kg DM, and the NE in wheat DDGS is typically between 2,032 and 2,268 kcal/kg DM (Cozannet et al., 2010a; Rosenfelder et al., 2013). The average DE, ME, and NE in wheat DDGS is slightly less than the average DE, ME, and NE in wheat (Table 2.1), most likely due to the greater fiber content of wheat DDGS compared with wheat (Rosenfelder et al., 2013).

Corn DDGS vs. Wheat DDGS

The DE and ME of wheat DDGS is comparable to the DE and ME in DDGS-DO, however, it is less than the DE and ME in DDGS-CV and DDGS-LF (Table 2.1). This is most likely due to the greater concentration of EE in DDGS-CV and DDGS-LF compared with wheat DDGS. The NE in wheat DDGS is less than the NE in DDGS-CV, which may be due to the lower EE and greater fiber content in wheat DDGS compared with DDGS-CV.

Wheat-corn DDGS

Kiarie et al. (2013) determined the DE (3,881 kcal/kg DM) and ME (3,669 kcal/kg DM) in DDGS derived from a mixture of wheat and corn; however, the ratio of wheat-corn was not indicated. More research needs to be conducted in order to determine the DE and ME in DDGS derived from mixtures of wheat and corn, especially on how the ratio of wheat-corn used in ethanol production may affect the DE and ME in wheat-corn DDGS.

SOURCES OF VARIATION IN DDGS

Shurson and Alghamdi (2008) discussed various factors affecting variability of conventional DDGS. One common assumption that is expressed is that the variation in corn composition can be one of the factors that leads to variation in DDGS composition (Belyea et al., 2004; Shurson and Algahmdi, 2008; Liu, 2010). However, Belyea et al. (2004) compared the coefficients of variation for composition of corn and DDGS and determined that the variation in DDGS composition is not related to the variation in corn composition. However, the standard deviations for corn DM, CP, crude fiber, EE, and ash were less than those for DDGS with greater than 10% oil (NRC, 2012), which indicates that variation is greater in DDGS compared with corn. Magnitude of variation can depend on how variation is expressed making it difficult to compare references.

The composition of solubles and the ratio of solubles added to distillers grains can also be a source of variation in composition of DDGS (Belyea et al., 2004; Knott et al., 2004; Han and Liu, 2010; Liu, 2010; Liu, 2011). The solubles fraction contains more EE compared with distillers grains (Knott et al., 2004), however, it also has greater variability (Liu, 2011). By the addition of solubles, DDGS EE may increase, which may have an effect on energy concentration (Knott et al., 2004; Shurson and Alghamdi, 2008). The amount of solubles added to distillers grains can also vary among ethanol plants (Liu, 2011).

The protein in DDGS is derived from corn and yeast (Belyea et al., 2004; Han and Liu, 2010; Liu, 2011), but the proportion of each is not well known. During fermentation, yeast utilize non-protein nitrogen as a N source to grow (Belyea et al., 2004). Yeast cannot degrade corn protein to utilize the N for growth because they lack the proteolytic enzymes to do so. Therefore, corn protein also contributes to DDGS protein (Belyea et al., 2004; Han and Liu, 2010). Han and Liu (2010) estimate that the contribution of yeast protein to DDGS protein is approximately 20% and approximately 80% is from the contribution of corn protein. More research is needed to understand the contribution of yeast protein and corn protein to DDGS protein.

Particle size can be another source of variation in DDGS. It is known that DDGS particle size can impact energy digestibility and flowability. Liu et al. (2012) determined that when particle size is decreased from 818 to 308 μm, each 25 μm decrease improved ME by 13.46 kcal/kg DM; however, flowability of DDGS is reduced as particle size decreases. Liu et al. (2012) determined that flowability was reduced when DDGS was ground to 594 μm and 308 μm when compared with 818 μm. Flowability can also be affected by fat content of DDGS. Increasing fat content of DDGS decreases flowability (Liu et al., 2012). More research is needed to determine the effects of particle size and fat content on flowability and DE and ME in DDGS.

CONCLUSION

More research is needed to understand the variability of nutrient composition and digestibility in DDGS. As previously discussed, variation in nutrient composition and digestibility in DDGS can be impacted by the starting feedstock used for ethanol production. Composition and digestibility of nutrients in feedstock, whether the feedstock is a mixture of grains, and possibly the year in which the feedstock was harvested are all sources of variation that may influence the composition and digestibility of nutrients in DDGS. The purpose of the experiments described in Chapter 3 and 4 of this thesis was to explore the variation of composition and digestibility of nutrients in DDGS.

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TABLES AND FIGURES

Table 2.1. Composition of corn, wheat, and distillers dried grains with solubles (DDGS) produced from corn and wheat fed to pigs[1], DM basis

	Corn		Wheat		Corn DDGS: DDGS-CV[2]		Corn DDGS: DDGS-LF[3]		Corn DDGS: DDGS-DO[4]		Wheat DDGS		Corn-wheat DDGS	
Item	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
DM, %	86.60	0.88	88.83	2.00	88.61	1.20	89.61	2.07	88.28	0.90	92.46	2.23	92.17	1.42
CP, %	8.53	0.64	15.03	2.89	30.48	1.08	32.11	2.26	33.11	2.40	39.44	3.79	34.97	4.16
Ash, %	1.08	-	1.99	0.20	4.95	0.50	5.01	0.72	5.41	0.39	5.44	1.19	4.48	0.83
AEE[5], %	-	-	-	-	12.66	-	9.54	1.98	-	-	-	-	-	-
EE[6], %	2.99	0.21	1.74	0.10	12.76	1.07	9.73	1.18	4.63	0.88	4.61	0.77	10.20	-
Crude fat, %	-	-	1.80	-	12.08	0.60	10.55	0.03	3.86	1.00	4.80	1.73	5.57	0.85
Crude fiber, %	-	-	2.40	-	7.87	0.90	8.29	0.88	8.69	-	7.95	0.49	7.80	ND
ADF, %	2.57	0.30	3.76	1.06	13.25	2.58	12.62	3.30	15.72	4.21	15.83	4.70	14.52	4.41
NDF, %	9.15	2.14	12.00	1.95	35.38	4.55	36.79	5.93	39.82	8.27	33.39	5.97	38.35	7.40
TDF[7], %	-	-	-	-	37.49	1.87	35.31	2.28	36.51	0.98	-	-	-	-
Indispensable AA, %														
Arg	0.40	0.04	0.69	0.14	1.37	0.09	1.41	0.12	1.46	0.02	1.58	0.17	1.54	0.26
His	0.24	0.02	0.34	0.07	0.82	0.05	0.84	0.07	0.91	0.02	0.89	0.09	0.85	0.11
Ile	0.28	0.03	0.53	0.10	1.16	0.05	1.18	0.09	1.20	0.08	1.37	0.14	1.32	0.17
Leu	0.91	0.13	0.99	0.21	3.64	0.35	3.72	0.42	4.10	0.03	2.73	0.22	3.12	0.06
Lys	0.27	0.01	0.40	0.07	0.94	0.14	1.02	0.13	0.96	0.18	0.71	0.24	0.90	0.22
Met	0.19	0.04	0.26	0.06	0.64	0.10	0.66	0.10	0.60	0.06	0.64	0.17	0.68	0.11
Phe	0.37	0.05	0.67	0.17	1.50	0.11	1.55	0.14	1.71	0.28	1.93	0.14	1.78	0.24
Thr	0.27	0.01	0.43	0.08	1.22	0.28	1.25	0.30	1.00	0.25	1.29	0.07	1.21	0.17
Trp	0.03	0.04	0.17	0.04	0.24	0.03	0.24	0.03	0.47	0.26	0.41	0.04	0.37	ND
Val	0.40	0.04	0.65	0.12	1.56	0.09	1.56	0.12	1.37	0.35	1.80	0.15	1.77	0.24

Table 2.1 (cont.)

					Corn DDGS									
	Corn		Wheat		DDGS-CV[2]		DDGS-LF[3]		DDGS-DO[4]		Wheat DDGS		Corn-wheat DDGS	
Item	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Dispensable AA, %														
Ala	0.57	0.06	0.49	0.05	2.26	0.25	2.27	0.19	2.44	0.06	1.47	0.05	1.82	0.07
Asp	0.57	0.13	0.73	0.12	2.05	0.22	2.07	0.19	2.13	0.09	2.06	0.20	2.01	0.31
Cys	0.16	0.01	0.38	0.10	0.59	0.13	0.56	0.11	0.59	0.03	0.73	0.30	0.81	0.16
Glu	1.43	0.21	3.27	2.06	5.08	1.09	5.25	0.83	5.10	0.47	11.19	1.24	8.62	3.80
Gly	0.34	0.02	0.57	0.08	1.25	0.08	1.23	0.07	1.36	0.05	1.68	0.08	1.46	0.31
Pro	0.74	-	1.40	0.23	2.40	0.23	2.49	0.17	2.45	0.13	3.87	0.38	3.13	0.64
Ser	0.39	0.10	0.64	0.14	1.33	0.24	1.38	0.20	1.52	0.08	1.94	0.15	1.69	0.42
Tyr	0.29	0.09	0.32	0.05	1.24	0.14	1.31	0.12	1.25	0.04	1.16	0.03	1.09	0.09
Lys:CP[8], %	3.23	0.16	2.69	0.13	3.09	0.48	3.30	0.48	2.93	0.49	1.84	0.60	2.50	0.72
GE, kcal/kg	4256	346.86	4382	59.87	5412	189.23	5296	218.44	5200	463.06	4856	260.05	5203	128.06
DE, kcal/kg	3820	379.72	3568	325.98	3980	164.76	3969	221.85	3556	403.56	3459	159.10	3881	-
ME, kcal/kg	3733	362.04	3446	434.87	3736	158.26	3750	202.97	3318	411.07	3241	138.59	3669	-
NE, kcal/kg	-	-	2020	-	2437	-	-	-	-	-	2150	166.88	-	-

[1]Data are sourced from Spiehs et al., 2002; Nyachoti et al., 2005; Stein et al., 2006; Pedersen et al., 2007; Widyaratne and Zijlstra, 2007; Lan et al., 2008; Emiola et al., 2009; Stein et al., 2009; Cozannet et al., 2010a; Cozannet et al., 2010b; Yang et al., 2010; Azarfar et al., 2011; Jacela et al., 2011; Anderson et al., 2012; Ayoade et al., 2012; Nitroyová et al., 2012; Almeida et al., 2013; Kerr et al., 2013; Kiarie et al., 2013; Rosenfelder et al., 2013; Curry et al., 2014; Guiterrez et al., 2014.

[2]DDGS-CV = conventional DDGS with >11% fat, DM basis.

[3]DDGS-LF = low-fat DDGS with <11% and >6% fat, DM basis.

[4]DDGS-DO = de-oiled DDGS with <6% fat, DM basis.

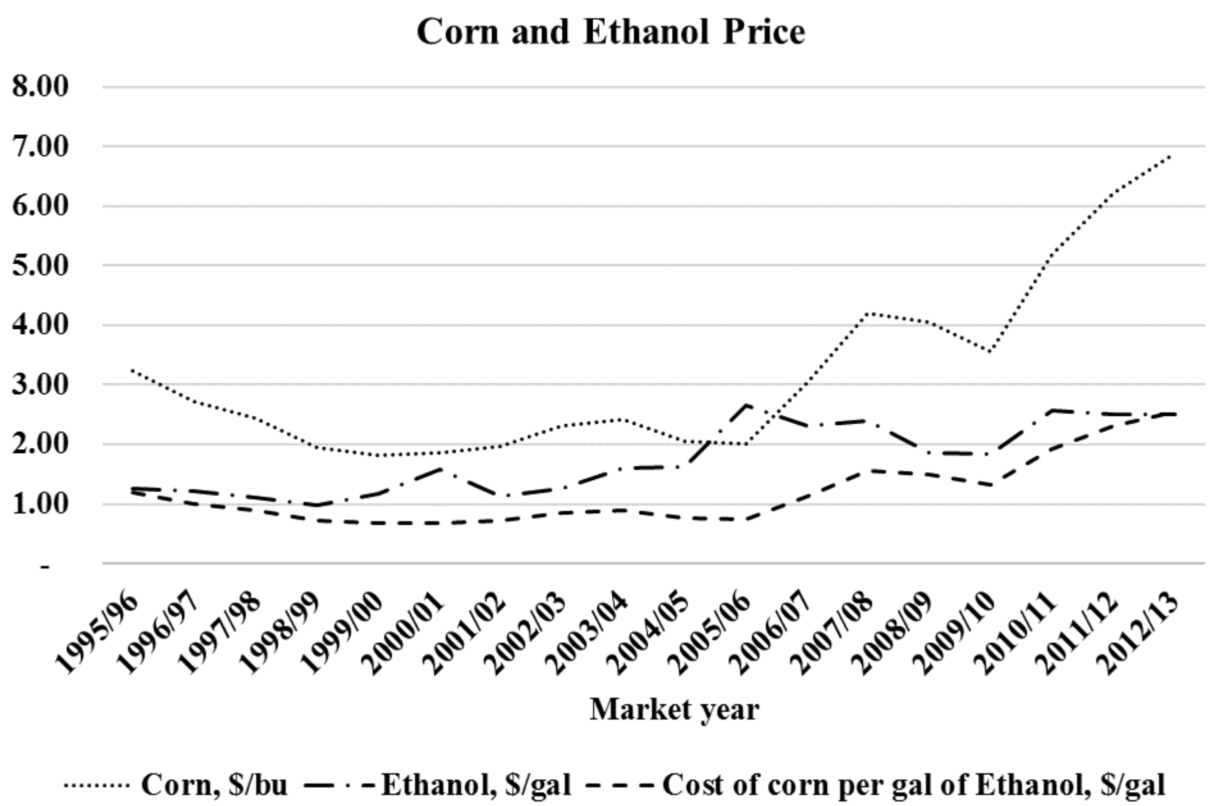
[5]AEE = acid hydrolyzed ether extract.

[6]EE = ether extract.

[7]TDF = total dietary fiber.

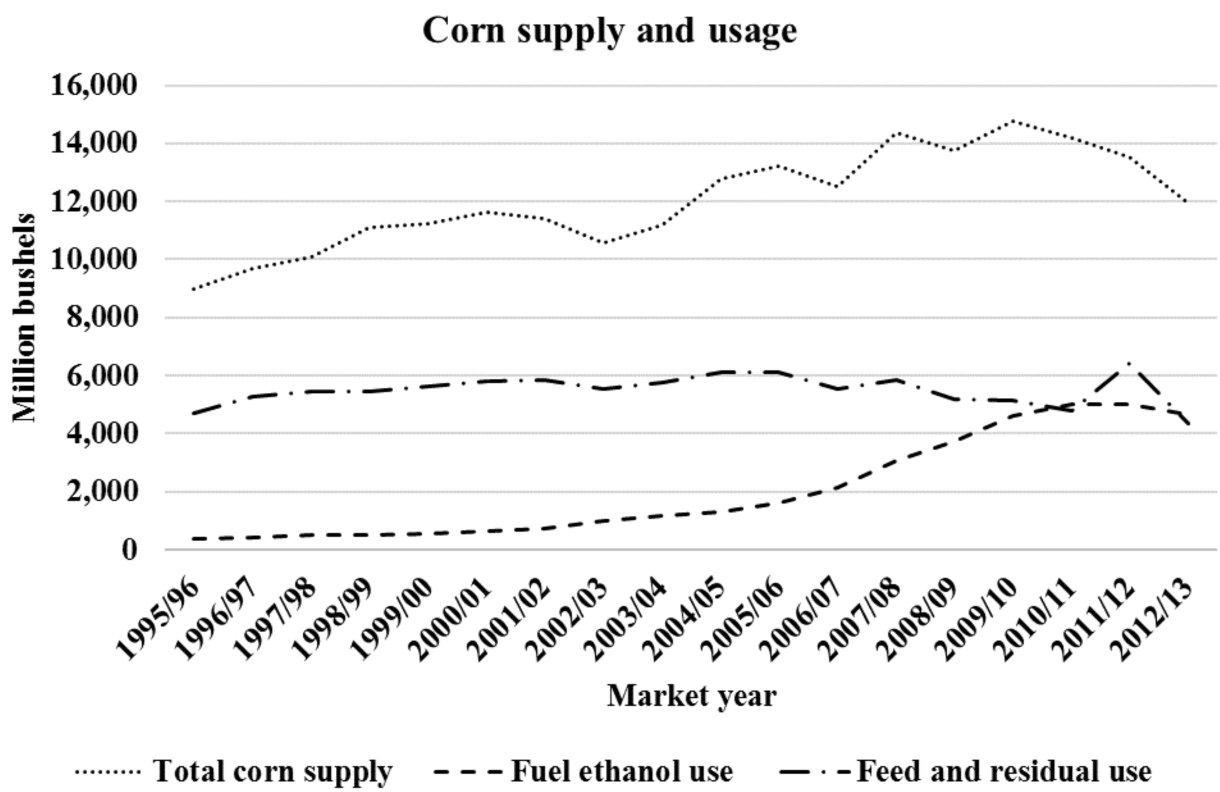
[8]Lys:CP ratio is the lysine concentration expressed as a percent of the CP concentration.

Figure 2.1. Corn and ethanol price from market year 1995/96 to market year 2012/13[1]



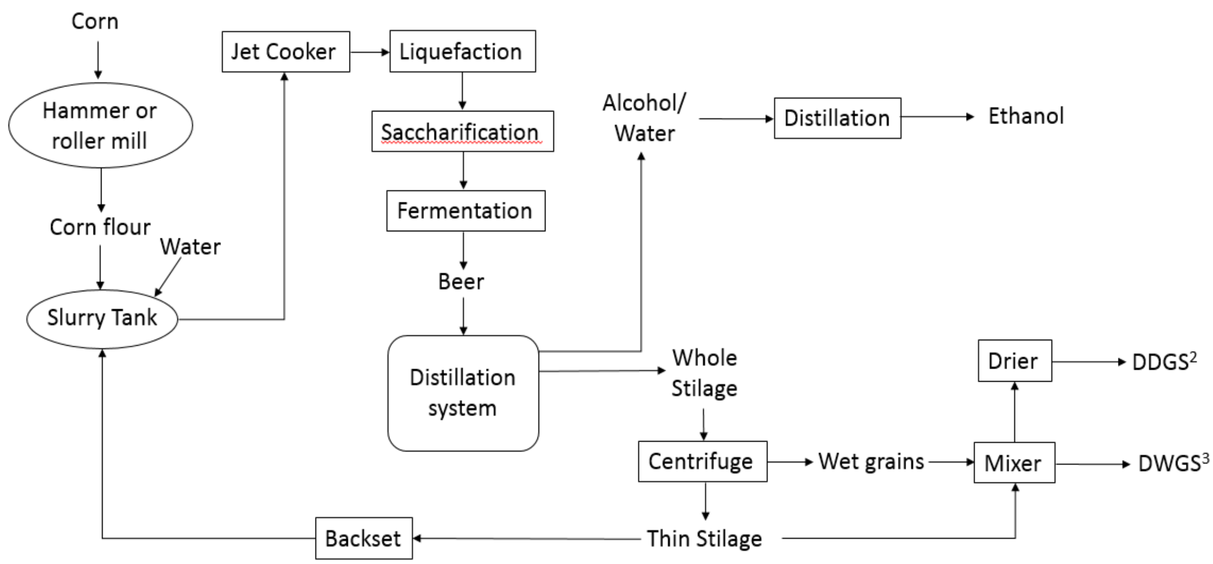
[1]Adapted from ERS, 2014 U.S. Bioenergy Statistics database. Available online: http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx#30041.

Figure 2.2. Total corn supply and the amount used for fuel ethanol and feed and residual use from market year 1995/96 to market year 2012/13[1]



[1]Adapted from ERS, 2014 U.S. Bioenergy Statistics database. Available online: http://www.ers.usda.gov/data-products/us-bioenergy-statistics.aspx#30041.

Figure 2.3. Process flow of a dry grind ethanol plant[1]



[1]Figure adapted from Rausch and Belyea, 2006 and Han and Liu, 2010.

[2]DDGS = distillers dried grains with solubles.

[3]DWGS = distillers wet grains with solubles.

CHAPTER 3

DIGESTIBLITY BY GROWING PIGS OF AMINO ACIDS IN EUROPEAN DISTILLERS DRIED GRAINS WITH SOLUBLES PRODUCED FROM MAIZE, WHEAT, OR MIXTURES OF WHEAT AND MAIZE

ABSTRACT

European ethanol plants may use wheat or maize or combinations of wheat and maize as feedstock. The distillers dried grains with solubles (DDGS) that is produced, therefore, may vary in composition and nutritional attributes according to the grain that was used in the production. There are, however, no data on how these differences influence the digestibility of AA in DDGS. Therefore, an experiment was conducted to compare the standardized ileal digestibility (SID) of AA by growing pigs in European DDGS produced from wheat, maize, or wheat-maize mixtures. Twelve barrows (average initial BW: 23.0 ± 2.2 kg) were surgically equipped with a T-cannula in the distal ileum and randomly allotted to a replicated 6 × 6 Latin square design with 6 diets and 6 periods. The 5 sources of European DDGS that were used in the experiment included wheat DDGS from 2011, wheat DDGS from 2012, wheat-80 (80% wheat and 20% maize) DDGS, wheat-70 (70% wheat and 30% maize) DDGS, and maize DDGS. A diet containing each source of DDGS as the sole source of AA was formulated and an N-free diet was used to determine basal endogenous losses of CP and AA. Results indicated that the SID of CP was greater ($P < 0.05$) in maize DDGS compared with wheat DDGS from 2011, wheat DDGS from 2012, and wheat-70 DDGS. The SID of all indispensable AA except Trp was also greater ($P < 0.05$) in maize DDGS compared with all other DDGS sources used in this experiment. For Trp,

the SID in wheat-80 DDGS, wheat DDGS from 2011, and wheat DDGS from 2012 were not different from maize DDGS, but were greater ($P < 0.05$) than in wheat-70 DDGS. The SID for all indispensable AA except Ile and Trp in wheat-70 DDGS were not different from the values calculated for wheat DDGS from 2011 and wheat DDGS from 2012, and no differences between SID values for AA in wheat DDGS from 2011 and wheat DDGS from 2012 were observed. In conclusion, the SID of AA in maize DDGS produced in Europe is greater than in European wheat DDGS and DDGS produced from mixtures of wheat and maize.

Keywords: amino acid digestibility, distillers dried grains with solubles, pigs

INTRODUCTION

Distillers dried grains with solubles (**DDGS**) is a by-product of cereal grain fermentation. In the United States, corn is the primary feedstock used in ethanol production, but European ethanol plants may use wheat or maize or combinations of wheat and maize as feedstock (Cozannet et al., 2010a). The quality of DDGS produced depends on many factors, including quality and genetic background of the starting feedstock, and variation in DDGS composition can occur among batches from the same production unit and among production units (Rosenfelder et al., 2013). Digestibility of AA in maize DDGS varies (Stein and Shurson, 2009), but the AA that is most variable in concentration and digestibility is Lys (Cozannet et al., 2010b; NRC, 2012; Rosenfelder et al., 2013). Greater variation in Lys digestibility may be a result of heat damage in some sources of DDGS (Pahm et al., 2008; Stein and Shurson, 2009; Almeida, et al., 2013). Wheat DDGS usually contains more CP and NDF, but less ether extract than maize DDGS, and variability in AA composition and digestibility among sources of wheat DDGS have been reported (Widyaratne and Zijlstra, 2008; Cozannet et al., 2010b; NRC, 2012). The concentration and digestibility of Lys tends to be less in wheat DDGS than in maize DDGS whereas the opposite is the case for Trp (Stein and Shurson, 2009). As a consequence, the AA composition of DDGS produced from mixtures of maize and wheat depends on the proportion of each source of cereal grain used. However, the composition and digestibility of AA in DDGS may be influenced not only by the feedstock used in the ethanol plant, but possibly also by the year in which the feedstock was grown because grain composition may vary from year to year. There are, however, limited data on how these differences influence the digestibility of AA in DDGS (Widyaratne and Zijlstra, 2007, 2008; Nitrayová et al., 2012; Kiarie et al., 2013). Therefore, an experiment was conducted to compare the standardized ileal digestibility (**SID**) of AA by growing pigs in European DDGS produced from wheat, maize, or wheat-maize mixtures.

MATERIALS AND METHODS

The Institutional Animal Care and Use Committee at the University of Illinois reviewed and approved the protocol for this experiment.

Animals, Housing, and Experimental Design

Twelve barrows (initial BW: 23.0 ± 2.2 kg) were surgically equipped with a T-cannula in the distal ileum (Stein et al., 1998). Pigs were randomly allotted to a replicated 6 × 6 Latin square design with 6 diets and 6 periods and housed individually in pens (1.2 × 1.5 m) with fully slatted tri-bar floors, solid-sided walls, a feeder, and a nipple drinker. Pens are located in a temperature controlled barn that has forced air fans and a propane heater.

Ingredients, Diets, and Feeding

Five European sources of DDGS were used: wheat DDGS from 2011, wheat DDGS from 2012, wheat-80 DDGS (80% wheat and 20% maize used as feedstock), wheat-70 DDGS (70% wheat and 20% maize used as feedstock), and maize DDGS (Table 1). Wheat DDGS from 2011 was manufactured in 2011 using UK wheat that was harvested in 2010. Wheat DDGS from 2012 was manufactured in 2012 using UK wheat that was harvested in 2012. Wheat-80 DDGS was manufactured in 2012 using approximately 80% UK wheat that was harvested in 2012 and approximately 20% maize that was harvested in France in 2012. Wheat-70 DDGS contained approximately 70% wheat and 30% maize that were harvested in Germany in 2012. Maize DDGS was manufactured in Hungary using maize that was harvested in Hungary in 2012. Six diets were prepared (Table 2 and 3). Five diets contained cornstarch, sucrose, and 50% of each of the 5 sources of DDGS as the only source of protein and AA. A N-free diet that was used to calculate basal endogenous losses of protein and AA was also formulated. Vitamins and minerals were added to all diets to meet or exceed requirements (NRC, 2012). Chromic oxide was included in all diets at 0.4% as an indigestible marker. Diets were sampled at time of mixing. All diets were fed in a meal form.

Pigs were fed diets at 3 times the estimated energy requirement for maintenance (i.e., 197 kcal ME per kg $^{0.60}$; NRC, 2012) in 2 equal meals per day. Water was available via a nipple drinker at all times for the duration of the experiment.

Date Recording and Sample Collection

At the beginning of each period, pigs were weighed to calculate the amount of daily feed allotted for that period. Each period was 7 d; the first 5 d was considered a diet adaptation period. On d 6 and 7, ileal digesta were collected for 8 h, by attaching a plastic bag to the T-cannula via a plastic auto-locking zip-tie (Stein et al., 1998). Bags were removed from the cannula and replaced with an empty bag and zip-tie whenever they were full or every 30 min. Ileal digesta were placed in individual, labeled containers immediately after collection. Containers were stored at -20°C to prevent bacterial breakdown of AA in the ileal digesta. At the end of each collection period, feed that was not consumed for that day was removed and pigs were deprived of feed overnight. The following morning, a new experimental diet was fed.

Chemical Analysis

At the conclusion of each period, ileal digesta were thawed, mixed within diet and animal, and a sub-sample was collected. Sub-samples of ileal digesta were lyophilized and ground prior to chemical analysis. Diets, ingredients, and ileal digesta were analyzed for DM (method 930.15; AOAC Int., 2007), CP (method 990.03; AOAC Int., 2007), and AA (method 982.30 E (a, b, c); AOAC Int., 2007). Diets and ileal digesta were also analyzed for chromium (method 990.08; AOAC Int., 2007). Ingredients were analyzed for ADF (method 973.18; AOAC Int., 2007) and NDF (Holst, 1973). Ingredients were analyzed for acid hydrolyzed ether extract that was analyzed by acid hydrolysis using 3*N* HCl (Sanderson, 1986) followed by crude fat extraction with petroleum ether (method 2003.06; AOAC Int., 2007) on a Soxtec 2050 automated analyzer (FOSS North America, Eden Prairie, MN).

Calculations and Statistical Analysis

The apparent ileal digestibility (**AID**) of CP and each AA in diets containing each source of DDGS was calculated. The DDGS was the only ingredient contributing CP and AA to the diets; therefore, the calculated digestibility values for the diets also represent the digestibility values for each ingredient. Basal endogenous losses of CP and each AA were determined by their appearance in ileal digesta obtained after feeding the N-free diet. The SID values were calculated by correcting AID of CP and each AA for the basal endogenous loss. Analyzed chromium and AA levels of each diet and ileal sample were used in calculations for AID. Previously published equations were used for all calculations (Stein et al., 2007).

Data were analyzed using the Proc MIXED procedure of SAS (SAS Inst. Inc., Cary, NC). The model for analysis of variance included pig and period as random effects and diet as a fixed effect. The LSMeans statement was used to calculate mean values for each diet. The pdiff option in Proc Mixed was used to separate treatment means that were significant. Orthogonal contrasts were conducted to compare wheat DDGS 2011 with wheat DDGS 2012, wheat-80 DDGS with wheat-70 DDGS and maize DDGS with all other ingredients. The experimental unit for all analyses was the pig, and an alpha level of 0.05 was used to determine significant differences among means.

RESULTS

All pigs were healthy for the duration of the experiment. The AID for CP was greater ($P < 0.05$) in maize DDGS, wheat-80 DDGS, and wheat DDGS from 2012 than in wheat-70 DDGS (Table 3.4). There was no difference in AID for CP between wheat DDGS from 2011 and wheat DDGS from 2012.

The AID for all indispensable AA except Trp and the mean of all indispensable AA was greater ($P < 0.05$) in maize DDGS than in all other ingredients. For Trp, the AID in wheat-80 DDGS, wheat DDGS from 2011, and wheat DDGS from 2012 was greater ($P < 0.05$) than in wheat-70 DDGS, but the AID of Trp in wheat-70 DDGS was not different from maize DDGS. The mean AID for indispensable AA in wheat-70 DDGS was less ($P < 0.05$) than in maize DDGS and wheat-80 DDGS, but not different from the mean AID for indispensable AA in wheat

DDGS from 2011 and wheat DDGS from 2012. The AID of all AA was not different between wheat DDGS 2011 and wheat DDGS 2012. Wheat-80 DDGS had greater AID of His, Ile, Leu, Phe, Thr, and mean indispensable AA compared with wheat-70 DDGS. The AID for all AA was greater ($P < 0.05$) in maize DDGS than in all other DDGS sources used in this experiment.

The SID for CP was greater ($P < 0.05$) in maize DDGS than in wheat DDGS from 2011, wheat DDGS from 2012, and wheat-70 DDGS, but not different from the SID for CP in wheat-80 DDGS (Table 3.5). The SID for all indispensable AA except Trp was greater ($P < 0.05$) in maize DDGS than in all other DDGS sources used in this experiment. For Trp, the SID in wheat-80 DDGS, wheat DDGS from 2011, and wheat DDGS from 2012 were not different from maize DDGS, but were greater ($P < 0.05$) than in wheat-70 DDGS. For His, Thr, Val, and the mean of indispensable AA, the SID was greater ($P < 0.05$) in wheat-80 DDGS than in wheat-70 DDGS, but not different from the SID in wheat DDGS from 2011 and wheat DDGS from 2012. The SID for all indispensable AA except Ile and Trp in wheat-70 DDGS were not different from the values calculated for wheat DDGS from 2011 and wheat DDGS from 2012. There were no differences in SID of all AA between wheat DDGS 2011 and wheat DDGS 2012. The SID of most AA was greater ($P < 0.05$) in wheat-80 DDGS compared with wheat-70 DDGS.

DISCUSSION

Composition of Distillers Dried Grains with Solubles

The concentration of DM in maize DDGS is in agreement with reported values of DM in corn DDGS produced in the U.S. (Stein et al., 2006; Pedersen et al., 2007; Stein et al., 2009). The concentration of DM in wheat DDGS from 2011 and wheat DDGS from 2012 was in agreement with the concentration of DM in wheat DDGS reported by Cozannet et al. (2010b), but was slightly less than the range of DM in wheat DDGS reported by Nyachoti et al. (2005). The concentration of DM in wheat-80 DDGS and wheat-70 DDGS were not different and the DM concentration in wheat-70 DDGS is in agreement with published values (Ayoade et al., 2012; Kiarie et al., 2013). To our knowledge, there are no published values for composition of DDGS derived from a mixture of 80% wheat and 20% maize.

The concentration of CP in wheat DDGS from 2011 was within the range of concentrations of CP in wheat DDGS reported by Nyachoti et al. (2005), but was less than the concentration of CP in wheat DDGS reported by Stein (2012). The composition of AA in wheat DDGS from 2011 and wheat DDGS from 2012 were less than reported values (Stein, 2012). The Lys:CP ratio for wheat DDGS from 2011 (1.64%) and for wheat DDGS from 2012 (1.53%) were less than the values (1.99% and 1.91%) calculated from the NRC (2012) and Cozannet et al. (2010b), respectively, but were in agreement with the value reported by Stein and Shurson (1.59%; 2009). The concentration of CP in wheat DDGS from 2011 and wheat DDGS from 2012 was greater than the concentration of CP in maize DDGS, which was expected. The concentration of CP in maize DDGS was greater than the concentration of CP in corn DDGS reported by Stein and Shurson (2009) and Kiarie et al. (2013), but was within the range of concentrations of CP in corn DDGS reported by Pedersen et al. (2007). The Lys:CP ratio for maize DDGS (2.90%) indicated that the maize DDGS used in this experiment was not heat damaged (Stein, 2007). The composition of AA in maize DDGS was in agreement with previously reported values for the composition of AA in corn DDGS (NRC, 2012; Stein, 2012). The concentration of CP in wheat-70 DDGS was less than reported values for concentration of CP in DDGS derived from a 7:3 wheat-corn mixture (Yang et al., 2010; Azarfar et al., 2011).

The concentrations of ADF and NDF in wheat DDGS from 2011 and wheat DDGS from 2012 were greater than the concentrations of ADF and NDF in wheat DDGS reported by Nyachoti et al. (2005), Cozannet et al. (2010b) and Stein (2012). The concentration of ADF and NDF in wheat-70 DDGS were less than the concentration of ADF and NDF in wheat-80 DDGS, which was expected because there is a greater concentration of wheat in the wheat-80 DDGS and wheat has a greater concentration of ADF and NDF compared with corn (NRC, 2012). The concentration of ADF in wheat-70 DDGS was less than the concentration of ADF in DDGS derived from a 7:3 wheat-corn mixture reported by Azarfar et al. (2011). However, the concentration of NDF in wheat-70 DDGS was less than the concentration of NDF in DDGS derived from a 7:3 wheat-corn mixture reported by Azarfar et al. (2011), but was in agreement with the concentration of NDF in DDGS derived from a 7:3 wheat-corn mixture reported by Yang et al. (2010). Wheat-70 DDGS and wheat-80 DDGS had ADF and NDF concentrations that were intermediate the values for wheat DDGS from 2011, wheat DDGS from 2012, and maize DDGS.

Wheat DDGS from 2012 was from a difficult harvest in the UK that produced wheat with low bushel weights and low starch content, however, wheat DDGS from 2012 contained nutrients in concentrations that were not different from that of wheat DDGS from 2011, which indicates that the bushel weight of the wheat grain may not influence the composition of DDGS produced after starch has been converted to ethanol.

The GE in wheat DDGS from 2011 and wheat DDGS from 2012 was less than reported values (Nyachoti et al., 2005; Nitroyová et al., 2012; Stein, 2012). The GE in wheat-70 DDGS was less than the GE in wheat-80 DDGS and was less than the published values of GE in DDGS derived from wheat-corn mixtures (Ayoade et al., 2012; Kiarie et al., 2013). The GE in maize

DDGS was also less than reported values of GE in corn DDGS (Stein et al., 2009; NRC, 2012; Stein, 2012).

Crude Protein and Amino Acid Digestibility

The SID of CP in wheat DDGS from 2011 and wheat DDGS from 2012 was slightly less than reported values (Cozannet et al., 2010b). The SID of each AA in wheat DDGS from 2011 and wheat DDGS from 2012 was also less than the SID of each AA in Canadian wheat DDGS reported by Widyaratne and Zijlstra (2007); however, the SID of each AA except Ala and Gly was within the range reported by Cozannet et al. (2010b) who also used European wheat DDGS. For wheat DDGS, the SID of Lys is most variable as indicated by a greater range of SID values (Cozannet et al., 2010b; Rosenfelder et al., 2013). The SID of all AA in wheat DDGS from 2011 was not different from the SID of all AA in wheat DDGS from 2012, which indicates that the digestibility of AA was not compromised by the poor quality of wheat from the 2012 harvest.

The SID of all AA except Arg, Lys, Met, Phe, Ala, Asp, and Gly were greater in wheat-80 DDGS than in wheat-70 DDGS, but the SID of all AA in wheat-70 DDGS was less than the SID of all AA in DDGS derived from a 7:3 wheat-corn mixture reported by Yang et al. (2010). To our knowledge there are no published values for SID of AA in wheat DDGS derived from an 8:2 wheat-corn mixture.

The SID of all AA except Trp and Glu were greater in maize DDGS compared with wheat DDGS from 2011 and wheat DDGS from 2012. This may be a result of to the greater ADF concentration in the wheat DDGS compared with maize DDGS. Greater concentrations of ADF can decrease digestibility of AA by restricting access for digestive enzymes (Cozannet et al., 2010b; Rosenfelder et al., 2013). In maize DDGS, the SID of all AA except Lys, Trp, Ala, and Gly, were comparable to published values (NRC, 2012; Almeida et al., 2013). The SID of

Lys in maize DDGS was less than reported values (Stein et al., 2006; Almeida et al., 2013). The mean of indispensable AA in maize DDGS was similar to reported values (Stein et al., 2006; Almeida et al., 2013). Maize DDGS had greater SID of most AA compared with wheat DDGS and wheat DDGS derived from a mixture of wheat and maize.

In conclusion, the nutrient composition and SID of AA in wheat DDGS from 2012 was not different from wheat DDGS from 2011. Maize DDGS had greater SID of AA compared with both wheat DDGS sources and DDGS derived from mixtures of maize and wheat. Additional research is needed to determine differences in nutrient composition and SID of AA in DDGS derived from mixtures of wheat and maize.

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TABLES

Table 3.1. Chemical composition of 5 European sources of distillers dried grains with solubles (DDGS) derived from maize, wheat or mixtures of maize and wheat, as-fed basis

	DDGS source				
Item	Wheat DDGS 2011	Wheat DDGS 2012	Wheat-80[1] DDGS	Wheat-70[1] DDGS	Maize DDGS
DM, %	89.53	90.71	90.00	90.25	88.71
CP, %	32.35	34.60	30.67	28.74	29.01
AEE,[2] %	5.74	5.19	5.53	6.01	9.60
Ash, %	4.36	5.13	4.53	6.49	4.34
ADF, %	24.49	24.83	21.86	17.89	13.35
NDF, %	33.68	35.24	33.66	30.42	27.13
GE, kcal/kg	4,483	4,549	4,566	4,373	4,636
Indispensable AA, %					
Arg	1.23	1.26	1.09	1.04	1.26
His	0.58	0.62	0.57	0.57	0.76
Ile	1.11	1.16	1.01	0.97	1.05
Leu	2.15	2.24	2.26	2.18	3.45
Lys	0.53	0.53	0.49	0.56	0.84
Met	0.46	0.46	0.43	0.42	0.60
Phe	1.45	1.56	1.36	1.26	1.43
Thr	0.96	0.98	0.89	0.90	1.07
Trp	0.32	0.34	0.28	0.27	0.23
Val	1.40	1.46	1.30	1.25	1.39
All indispensable AA	10.19	10.61	9.68	9.42	12.08
Lys:CP ratio,[3] %	1.64	1.53	1.60	1.95	2.90
Dispensable AA, %					
Ala	1.21	1.26	1.36	1.30	2.13
Asp	1.59	1.63	1.53	1.53	1.89
Cys	0.61	0.60	0.52	0.49	0.55
Glu	8.47	9.09	7.11	6.37	5.21
Gly	1.30	1.35	1.19	1.11	1.15
Pro	2.85	3.07	2.56	2.33	2.36
Ser	1.44	1.47	1.29	1.21	1.42
All dispensable AA	17.47	18.47	15.56	14.34	14.71

[1]Wheat-80 DDGS = DDGS derived from 80% wheat and 20% maize; wheat-70 DDGS = DDGS derived from 70% wheat and 30% maize.

[2]AEE = acid hydrolyzed ether extract.

[3]The Lys:CP ratio was calculated by expressing the concentration of Lys in each sample as a percentage of the concentration of CP (Stein et al., 2009).

Table 3.2. Ingredient composition of experimental diets, as-fed basis

	Diets					
Ingredient, %	Wheat DDGS[1] 2011	Wheat DDGS 2012	Wheat-80[2] DDGS	Wheat-70[2] DDGS	Maize DDGS	N-free
Wheat DDGS from 2011	50.0	-	-	-	-	-
Wheat DDGS from 2012	-	50.0	-	-	-	-
Wheat-80 DDGS	-	-	50.0	-	-	-
Wheat-70 DDGS	-	-	-	50.0	-	-
Maize DDGS	-	-	-	-	50.0	-
Cornstarch	25.5	25.5	25.5	25.5	25.5	67.8
Soybean oil	2.0	2.0	2.0	2.0	2.0	4.0
Sucrose	20.0	20.0	20.0	20.0	20.0	20.0
Limestone	1.4	1.4	1.4	1.4	1.4	0.6
Salt	0.4	0.4	0.4	0.4	0.4	0.4
Monocalcium phosphate	-	-	-	-	-	2.0
Solka Floc[3]	-	-	-	-	-	4.0
Magnesium oxide	-	-	-	-	-	0.1
Potassium carbonate	-	-	-	-	-	0.4
Chromic oxide	0.4	0.4	0.4	0.4	0.4	0.4
Vitamin-mineral premix[4]	0.3	0.3	0.3	0.3	0.3	0.3

[1]DDGS = distillers dried grains with solubles.

[2]Wheat-80 DDGS = DDGS derived from 80% wheat and 20% maize; wheat-70 DDGS = DDGS derived from 70% wheat and 30% maize.

[3]Fiber Sales and Development Corp., Urbana, OH.

[4]Provided the following per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D_3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu as copper sulfate and copper chloride, 20 mg; Fe as ferrous sulfate, 126 mg; I as ethylenediamine dihydriodide, 1.26 mg; Mn as manganese sulfate, 60.2 mg; Se as sodium selenite and selenium yeast, 0.3 mg; and Zn as zinc sulfate, 125.1 mg.

Table 3.3. Chemical composition of experimental diets, as-fed basis

	DDGS[1] source					
Item	Wheat DDGS 2011	Wheat DDGS 2012	Wheat-80[2] DDGS	Wheat-70[2] DDGS	Maize DDGS	N-free
DM, %	91.49	92.46	91.83	92.27	91.77	91.47
CP, %	17.29	17.65	15.09	14.54	14.94	1.13
Indispensable AA, %						
Arg	0.65	0.63	0.51	0.52	0.63	0.01
His	0.31	0.31	0.27	0.29	0.38	<0.01
Ile	0.60	0.58	0.48	0.49	0.53	0.01
Leu	1.15	1.14	1.10	1.10	1.75	0.04
Lys	0.29	0.27	0.23	0.29	0.42	<0.02
Met	0.23	0.21	0.19	0.20	0.30	<0.01
Phe	0.77	0.79	0.66	0.64	0.72	0.02
Thr	0.51	0.50	0.43	0.45	0.54	0.01
Trp	0.18	0.17	0.14	0.13	0.11	<0.02
Val	0.76	0.74	0.62	0.64	0.70	0.02
Dispensable AA, %						
Ala	0.65	0.65	0.66	0.66	1.08	0.03
Asp	0.85	0.83	0.73	0.78	0.96	0.02
Cys	0.32	0.30	0.25	0.25	0.28	<0.01
Glu	4.51	4.61	3.43	3.23	2.64	0.06
Gly	0.70	0.69	0.58	0.56	0.58	0.01
Pro	1.56	1.58	1.24	1.20	1.19	0.03
Ser	0.76	0.76	0.63	0.61	0.72	0.02

[1]DDGS = distillers dried grains with solubles.

[2]Wheat-80 DDGS = DDGS derived from 80% wheat and 20% maize; wheat-70 DDGS = DDGS derived from 70% wheat and 30% maize.

Table 3.4. Apparent ileal digestibility by growing pigs of DM, CP, and AA in 5 European sources of distillers dried grains with solubles (DDGS) derived from maize, wheat, or mixtures of wheat and maize[1]

	DDGS source						*P*-value		
	1	2	3	4	5				
Item	Wheat DDGS 2011	Wheat DDGS 2012	Wheat-80[2] DDGS	Wheat-70[2] DDGS	Maize DDGS	SEM	1 vs 2	3 vs 4	5 vs all other
CP, %	51.87^{bc}	53.44^{ab}	53.40^{ab}	48.22^{c}	57.43^{a}	2.00	0.54	0.07	0.01
Indispensable AA, %									
Arg	66.08^{b}	66.79^{b}	65.93^{b}	65.66^{b}	76.05^{a}	3.26	0.67	0.93	<0.01
His	62.86^{bc}	63.19^{bc}	65.22^{b}	60.53^{c}	74.06^{a}	1.66	0.69	0.04	<0.01
Ile	63.27^{b}	62.70^{b}	64.28^{b}	57.39^{c}	69.91^{a}	1.64	0.99	<0.01	<0.01
Leu	68.70^{c}	68.09^{c}	73.36^{b}	68.43^{c}	83.76^{a}	1.35	0.95	0.01	<0.01
Lys	21.27^{b}	15.91^{b}	18.75^{b}	19.94^{b}	50.61^{a}	3.71	0.50	0.84	<0.01
Met	66.40^{bc}	64.64^{c}	68.23^{b}	65.17^{bc}	80.57^{a}	1.50	0.56	0.13	<0.01
Phe	68.94^{b}	68.20^{bc}	69.59^{b}	65.22^{c}	74.05^{a}	1.66	0.90	0.05	<0.01
Thr	50.77^{b}	49.83^{bc}	52.15^{b}	45.91^{c}	60.61^{a}	2.09	0.99	0.03	<0.01
Trp	54.64^{a}	51.54^{ab}	53.46^{a}	43.71^{c}	47.22^{bc}	2.23	0.46	<0.01	0.12
Val	60.46^{bc}	59.24^{bc}	61.78^{b}	57.16^{c}	69.72^{a}	1.75	0.83	0.06	<0.01
Mean	61.42^{bc}	60.80^{bc}	63.49^{b}	58.65^{c}	73.22^{a}	1.69	0.99	0.04	<0.01
Dispensable AA, %									
Ala	43.50^{c}	42.55^{c}	53.23^{b}	50.29^{b}	70.16^{a}	2.51	0.99	0.43	<0.01
Asp	39.81^{bc}	38.32^{c}	44.84^{b}	41.19^{bc}	61.61^{a}	2.58	0.94	0.29	<0.01
Cys	61.94^{b}	61.53^{b}	62.61^{b}	55.69^{c}	67.98^{a}	1.82	0.90	<0.01	<0.01
Glu	80.91^{ab}	91.99^{a}	81.53^{a}	76.80^{c}	79.21^{b}	0.98	0.33	<0.01	0.30
Gly	28.25^{a}	29.12^{a}	29.02^{a}	17.57^{b}	19.23^{ab}	5.39	0.72	0.12	0.31
Ser	64.79^{b}	66.25^{b}	66.94^{b}	60.01^{c}	73.12^{a}	1.68	0.37	<0.01	<0.01
Mean	66.06^{a}	67.10^{a}	67.46^{a}	61.37^{b}	68.19^{a}	1.58	0.50	<0.01	0.12
All AA	64.13^{b}	64.55^{b}	65.60^{b}	60.18^{c}	70.66^{a}	1.60	0.67	0.02	<0.01

$^{a\text{-}c}$Within a row, means without a common superscript differ ($P < 0.05$).

[1]Each least square mean represents at least 10 observations.

[2]Wheat-80 DDGS = DDGS derived from 80% wheat and 20% maize; wheat-70 DDGS = DDGS derived from 70% wheat and 30% maize.

Table 3.5. Standardized ileal digestibility by growing pigs of CP and AA in 5 European sources of distillers dried grains with solubles (DDGS) derived from maize, wheat, or mixtures of wheat and maize[1]

	DDGS source								
	1	2	3	4	5		*P*-value		
Item	Wheat DDGS 2011	Wheat DDGS 2012	Wheat-80[2] DDGS	Wheat-70[2] DDGS	Maize DDGS	SEM	1 vs 2	3 vs 4	5 vs all other
CP, %	61.53^{b}	63.00^{b}	64.50^{ab}	59.79^{b}	68.64^{a}	2.00	0.56	0.10	<0.01
Indispensable AA, %									
Arg	72.63^{b}	73.63^{b}	74.31^{b}	73.93^{b}	82.83^{a}	3.26	0.62	0.96	<0.01
His	68.02^{bc}	68.40^{bc}	71.16^{b}	66.09^{c}	78.28^{a}	1.66	0.67	0.03	<0.01
Ile	68.00^{b}	67.64^{b}	70.20^{b}	63.22^{c}	75.27^{a}	1.64	0.92	<0.01	<0.01
Leu	72.89^{c}	72.37^{c}	77.76^{b}	72.85^{c}	86.52^{a}	1.35	0.99	0.01	<0.01
Lys	32.59^{b}	28.20^{b}	33.07^{b}	31.36^{b}	58.45^{a}	3.71	0.62	0.72	<0.01
Met	70.23^{bc}	68.88^{c}	72.89^{b}	69.62^{bc}	83.51^{a}	1.50	0.69	0.11	<0.01
Phe	75.62^{bc}	74.77^{bc}	77.41^{b}	73.32^{c}	81.21^{a}	1.66	0.93	0.07	<0.01
Thr	60.78^{bc}	60.14^{bc}	64.05^{b}	57.34^{c}	70.09^{a}	2.09	0.93	0.02	<0.01
Trp	62.19^{a}	59.63^{a}	63.21^{a}	54.26^{b}	59.62^{a}	2.21	0.56	<0.01	0.86
Val	65.63^{bc}	64.61^{bc}	68.14^{b}	63.35^{c}	75.35^{a}	1.75	0.89	0.05	<0.01
Mean	67.49^{bc}	67.06^{bc}	70.67^{b}	65.67^{c}	78.67^{a}	1.69	0.93	0.04	<0.01
Dispensable AA, %									
Ala	52.84^{c}	51.98^{c}	62.46^{b}	59.56^{b}	75.79^{a}	2.51	0.99	0.43	<0.01
Asp	48.00^{c}	46.80^{c}	54.42^{b}	50.20^{bc}	68.88^{a}	2.58	0.99	0.23	<0.01
Cys	67.80^{b}	67.85^{b}	70.14^{b}	63.26^{c}	74.70^{a}	1.81	0.77	<0.01	<0.01
Glu	82.89^{a}	83.96^{a}	84.16^{a}	79.60^{b}	82.62^{a}	0.98	0.33	<0.01	0.95
Gly	49.66	51.07	54.96	44.56	45.15	5.39	0.66	0.16	0.50
Ser	71.04^{bc}	72.56^{b}	74.50^{b}	67.85^{c}	79.73^{a}	1.68	0.36	<0.01	<0.01
Mean	71.66^{ab}	72.73^{a}	74.44^{a}	68.60^{b}	75.18^{a}	1.58	0.49	<0.01	0.05
All AA	69.93^{bc}	70.43^{bc}	72.66^{b}	67.32^{c}	76.90^{a}	1.60	0.65	0.02	<0.01

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

[1]Each least square mean represents at least 10 observations. Values for standardized ileal digestibility were calculated by correcting apparent ileal digestibility values for basal endogenous losses (g/kg of DMI), which were determined by feeding pigs a N-free diet; CP, 18.24; Arg, 0.47; His, 0.17; Ile, 0.31; Leu, 0.53; Lys, 0.36; Met, 0.10; Phe, 0.56; Thr, 0.56; Trp, 0.15; Val, 0.43; Ala, 0.66; Asp, 0.76; Cys, 0.21; Glu, 0.98; Gly, 1.64; Ser, 0.52.

[2]Wheat-80 DDGS = DDGS derived from 80% wheat and 20% maize; wheat-70 DDGS = DDGS derived from 70% wheat and 30% maize.

CHAPTER 4

ENERGY DIGESTIBILITY IN 23 SOURCES OF DISTILLERS DRIED GRAINS WITH SOLUBLES FED TO PIGS

ABSTRACT

In the United States, the primary feedstock for ethanol production is corn. Illinois is one the major corn producers in the nation and much of that corn is used to produce ethanol. The resulting co-product is distillers dried grains with solubles (DDGS). In recent years, ethanol plants have been centrifuging solubles and the resulting DDGS contains more protein and fiber, but less fat. Therefore, the purpose of this experiment was to determine if the concentration of DE and ME in DDGS produced in and around Illinois varied among plants. Twenty-four barrows (average initial BW: 28.1 ± 1.8 kg) were randomly allotted to 1 of 24 dietary treatments in a 24 × 8 Youden square design with 24 diets and 8 periods. Approximately 250 kg of DDGS were procured from 11 ethanol plants in IL, 4 ethanol plants in IN, 4 ethanol plants in IA, 2 ethanol plants in MO, and 2 ethanol plants in WI. Twenty-four diets were formulated: 1 diet containing 97.8% corn and 23 diets containing 40% of each source of DDGS. Each period consisted of a 7 d diet adaptation period and feces and urine were collected during the following 5 d based on the marker to marker approach. Results indicated that DDGS had high variability in concentration of ADF, NDF, and lignin (CV = 18.01, 10.09, and 34.74%, respectively). There was a wide range of particle size (266 to 930 μm) and bulk density (368 to 548 g/L) observed among the 23 sources of DDGS. The concentration of acid hydrolyzed ether extract ranged from 5.3 to 10.6%

indicating that some ethanol plants were centrifuging solubles to remove the corn oil from the solubles. The DE, ME, ATTD of GE, and ATTD of N in DDGS were different ($P < 0.05$) among sources. Correlation coefficients among and between chemical and physical components and DE and ME were determined. Prediction equations for DE and ME in DDGS were generated, but the accuracy with which DE and ME could be predicted was relatively low. In conclusion, DDGS procured from IL and surrounding states vary in concentration of ether extract, but more research is needed to generate prediction equations that can accurately predict DE and ME in DDGS.

Keywords: distillers dried grains with solubles, energy, pigs

INTRODUCTION

Illinois produces approximately 7% of all market pigs (USDA, 2014b) and approximately 20% of the corn in the United States (USDA, 2014a). Much of the corn is used for ethanol production and the resulting distillers dried grains with solubles (**DDGS**) is fed to pigs in IL and surrounding states. Swine producers in IL may also purchase DDGS from ethanol plants located close to the IL state line in the surrounding states. Conventional DDGS contains approximately 27% CP, 10% fat, 9% ADF, and 25% NDF (Stein and Shurson, 2009), and up to 45% DDGS may be included in diets fed to growing-finishing pigs without significantly reducing pig performance (Cromwell et al., 2011). However, different processing technologies of corn grain are used in the industry, which may result in production of DDGS with different concentrations of energy and nutrients (NRC, 2012). The concentration of DE and ME in conventional sources of DDGS is approximately 3,500 and 3,350 kcal/kg, respectively (Stein and Shurson, 2009), but it is possible that DE and ME differ among sources of DDGS produced using different processing technologies. In recent years, ethanol plants have been extracting oil by centrifugation from solubles or from DDGS by solvent extraction using ethanol or hexane (Jacela et al., 2011; Rosentrater et al., 2012; Kerr et al., 2013). This results in reduced ether extract (**EE**) and possibly reduced concentrations of DE and ME (Kerr et al., 2013). If that is the case, swine producers may purchase DDGS that contains less energy than expected, which may result in inaccuracies in diet formulations. Ultimately, this may also result in poorer performance of pigs fed DDGS-containing diets, which may contribute to a reduced perception among swine producers of the value of DDGS. It was, therefore, the objective of this experiment to determine if the concentrations of DE and ME in DDGS produced in and around IL vary among plants.

MATERIALS AND METHODS

Selection of Distillers Dried Grains with Solubles

Sources of DDGS were procured from 11 ethanol plants in IL, 4 ethanol plants in IN, 4 ethanol plants in IA, 2 ethanol plants in MO, and 2 ethanol plants in WI. Therefore, a total of 23 sources of DDGS were procured. Each sample (approximately 250 kg) was clearly labeled on arrival at the University of Illinois, and stored at approximately 15^{o}C.

Animals, Housing, Experimental Design, and Diets

A total of 24 growing barrows (Genetiporc, Alexandria, MN) with an average initial BW of 28.1 ± 1.8 kg were used in this experiment. Pigs were randomly allotted to 1 of 24 dietary treatments in a 24 × 8 Youden square design with 24 diets and 8 periods. Pigs were placed in metabolism crates that are equipped with a feeder and a nipple drinker, slatted floors, a screen floor, and a urine tray. The crates allow for total, but separate, collection of urine and feces from each individual pig.

A total of 24 diets were formulated and the basal diet was based on corn, minerals, and vitamins (Tables 4.1 and 4.2). Twenty-three additional diets were formulated by mixing corn and 40% of each source of DDGS. Vitamins and minerals were included in all diets to meet current requirements (NRC, 2012). An AA supplement was also formulated to contain 76, 16, and 8% Lys, Thr, and Trp, respectively.

Feeding and Sample Collection

Diets were provided daily in 2 equal meals in the amount of approximately 90% of ad libitum intake. Pigs were allowed ad libitum access to water throughout the experiment. The initial 7 d were considered an adaptation period to the diet. The AA supplement was provided during the adaptation period at 25 g per d and fed in 2 equal portions that were mixed into each pig's meal. Following the adaptation period, urine and feces were collected during the following 5 d according to standard procedures using the marker to marker approach (Adeola, 2001). Urine was collected once daily in urine buckets over a preservative of 50 mL of 3*N* HCl, the weights of the collected urine were recorded, and 20% of the collected urine were stored at -20^{o}C. Fecal samples were collected twice daily and stored at -20^{o}C. At the conclusion of the experiment, urine samples were thawed and mixed within animal and diet and subsamples were collected for chemical analysis. Fecal samples were also thawed and mixed within animal and diet, weighed, mixed with water to create a homogenous slurry, weighed and subsampled. Each subsample was weighed and used for chemical analysis.

Chemical Analysis

Fecal subsamples were dried in a forced air oven and finely ground prior to analysis. Samples of all ingredients, diets, and feces were analyzed for DM and ash by oven drying at 135°C for 2 h (method 930.15; AOAC Int., 2007) and dry ash at 600°C for 2 h and 45 min (method 942.05; AOAC Int., 2007), respectively. Concentrations of CP were analyzed in samples of ingredients, diets, feces, and urine using a combustion procedure (method 990.03; AOAC Int., 2007) on an Elementar Rapid N-cube protein/nitrogen apparatus (Elementar Americas Inc., Mt. Laurel, NJ). Aspartic acid was used as a calibration standard and CP was calculated as N × 6.25. The concentration of acid hydrolyzed ether extract (AEE) in ingredients were analyzed (method 954.02, AOAC Int., 2006). Gross energy was determined in all samples using bomb calorimetry (Model 6300, Parr Instruments, Moline, IL). Benzoic acid was used as the standard for calibration. Urine samples were prepared for GE analysis as previously outlined (Kim et al., 2009). All ingredients were analyzed for AA (Method 982.30 E [a, b, c]; AOAC Int., 2007), Ca, P, Cu, Fe, Mg, Mn, K, Se, Na, S, Zn, and Cl (Method 975.03; AOAC Int., 2007), and starch and lignin (Method 76-13; AACC Int., 2000; Method 973.18 (A-D); AOAC Int., 2006). Diets and ingredients were also analyzed for concentrations of ADF and NDF using Method 973.18 (AOAC Int., 2007) and Holst (1973), respectively. The bulk density (Cromwell et al., 2000) and particle size (ANSI/ASAE, 2008) of each source of DDGS were determined.

Calculations and Data Analysis

Hemicellulose and cellulose were calculated using published equations (NRC, 2012). The apparent total tract digestibility (**ATTD**) of energy, N, DM, and OM, and the concentration of DE and ME in each diet were calculated (Adeola, 2001). The concentrations of DE and ME in the corn diet were then divided by the inclusion rate of corn in that diet to calculate the concentration of DE and ME in corn. These values were used to calculate the contribution of corn to the corn-DDGS diets and the digestibility of energy and nutrients and the concentration of DE and ME in each source of DDGS was calculated by difference (Adeola, 2001). These procedures were also used to determine N balance for each diet and ingredient.

Data were analyzed using the MIXED procedure in SAS (SAS Institute Inc., Cary, NC). Pig was the experimental unit for all analyses. The model included diet as fixed effect and pig and period as random effects. Outliers were tested using the UNIVARIATE procedure. One outlier was removed in the diet calculations of ME and N retention. One outlier was removed in the ingredient calculations of ME. One outlier was removed for 6 ingredient calculations of N output in the urine and N retention and 2 outliers were removed from 2 ingredient calculations of N output in the urine and N retention. One outlier was removed for the ingredient calculation of ATTD of N. The LSMeans procedure of SAS was used to calculate the least squares means. If differences were detected, the PDIFF option with the Tukey's adjustment was used to separate the means. An alpha level of 0.05 was used to assess significance among means.

Correlation coefficients (r) among chemical components and between chemical composition and DE and ME of ingredients were determined using PROC CORR of SAS (SAS Institute Inc., Cary, NC). The PROC REG function of SAS (SAS Institute Inc., Cary, NC) was used to develop prediction equations as described by Sulabo and Stein (2013). The conceptual predictive criterion [**C(p)**], R^2, Akaike information criterion (**AIC;** measure of fit), and root mean square error (**RMSE;** measure of precision) were all considered in the development of the prediction equations. The optimal model was selected based on the following criteria: the C(p) is similar to p (p = the number of variables in the model + 1), low AIC, low RMSE, and high R^2.

RESULTS

Composition of Distillers Dried Grains with Solubles

On average, the DDGS contained 90.36, 5.98, 29.94, and 7.92% DM, ash, CP, and AEE, respectively (Table 4.3). There was greater variation in the concentration of ash (CV = 12.79%) and AEE (CV = 16.26%) compared with the concentration of DM and CP (CV = 1.20 and 5.89, respectively). The GE in DDGS ranged from 4,335 to 4,934 kcal/kg, but was on average 4,556 kcal/kg. The bulk density ranged from 368 to 548 g/L and the particle size ranged from 266 to 930 μm. Corn contained 88.58, 1.28, 8.57, and 3.79% DM, ash, CP, and AEE, respectively. Corn contained 3,938 kcal/kg of GE, had a bulk density of 611 g/L, and had an 885 μm particle size.

On average, the DDGS had a concentration of indispensable AA, dispensable AA, and all AA of 12.28, 13.11, and 25.38%, respectively (Table 4.4). The average concentration of Lys, Trp, and Met were 0.96, 0.18, and 0.55%, respectively. There was greater variability in the concentration of Lys, Trp, and Met compared with all other AA as indicated by the greater CV. Corn had a concentration of indispensable AA, dispensable AA, and all AA of 3.60, 3.96, and 7.17%, respectively. The concentration of Lys, Trp, and Met were 0.31, 0.06, and 0.17%, respectively.

The concentrations of ADF and NDF in DDGS were on average, 13.58 and 28.43%, respectively (Table 4.5). The concentration of lignin, hemicellulose, and cellulose in DDGS were on average 3.92, 14.84, and 9.66%, respectively. There was greater variability in the concentration of lignin (CV = 34.74%) compared with ADF, NDF, hemicellulose, and cellulose (CV = 18.01, 10.09, 15.43, and 14.28%, respectively). The concentration of starch (1.33% on average) had the greatest variability (CV = 126.56%).

On average, DDGS had greater concentration of K (1.05%) than of Ca (0.04%), P (0.79%), Na (0.20%), Mg (0.29%), and S (0.70%; Table 4.6). The concentration of Ca, Na, and S had greater variability compared with the concentration of P, K, and Mg. On average, DDGS had greater concentration of Fe (80.10 mg/kg) than of Zn (64.29 mg/kg), Se (4.33 mg/kg), Mo (0.84 mg/kg), Mn (15.74 mg/kg) and Cu (6.65 mg/kg). The variability was greatest in the concentration of Mo (CV = 41.97%) compared with Fe, Zn, Se, Mn, and Cu.

Digestibility of Nutrients and Concentration of DE and ME

Diets containing DDGS had an average concentration of DE of 3,223 kcal/kg, with a range from 3,096 to 3,342 kcal/kg (Table 4.7). The average concentration of ME in diets containing DDGS was 3,027 kcal/kg with a range from 2,914 to 3,173 kcal/kg. There were differences ($P < 0.01$) in concentrations of DE and ME in diets containing DDGS. The corn diet had concentrations of DE and ME of 3,329 and 3,182 kcal/kg, respectively.

The ATTD of GE in diets containing DDGS was on average 79.2% with a range from 77.4 to 81.4%. The corn diet had an ATTD of GE and an ATTD of N of 86.3 and 77.1%, respectively. The N retention in pigs fed the corn diet was 40.9%. The average N retention from pigs fed the diets containing DDGS was 42.4%; however, there were differences ($P < 0.01$) among diets containing DDGS. The ATTD of N in diets containing DDGS was on average 80.1% with a range from 75.0 to 83.1%. The ATTD of GE and N were different ($P < 0.01$) among diets containing DDGS. The range for ATTD of DM (78.6 to 82.6%) was in agreement with the range for the ATTD of OM (79.1 to 83.4%), and there were differences ($P < 0.01$) in ATTD of DM and ATTD of OM among diets containing DDGS.

The DDGS had an average DE of 3,474 kcal/kg DM with a range from 3,145 to 3,786 kcal/kg DM (Table 4.8). The average ME in DDGS was 3,173 kcal/kg DM (2,880 to 3,598 kcal/kg DM). The concentrations of DE and ME differed ($P < 0.01$) among DDGS sources. Corn contained 3,842 and 3,673 kcal/kg DM of DE and ME, respectively. The ATTD of GE in corn was 86.4%. The ATTD of GE in DDGS ranged from 62.6 to 75.4% and was on average 68.9%.

The N intake from pigs fed DDGS ranged from 31.5 to 42.9 g/d. The amount of N excreted in feces and urine from pigs fed DDGS ranged from 5.6 to 8.7 g/d and 8.0 to 18.5 g/d, respectively. The amount of N retained in pigs fed DDGS ranged from 12.3 to 21.2 g/d, but was on average 17.1 g/d. The N retention in pigs fed DDGS ranged from 32.4 to 58.5%, but was on average 44.5%. There were differences ($P \leq 0.01$) in N intake, N excreted in feces and urine, N retained, and N retention from pigs fed DDGS. The ATTD of N in DDGS ranged from 74.0 to 85.2% and was on average 81.2%. Pigs fed corn had a N intake of 25.8 g/d and excreted 5.9 and 8.8 g/d in feces and urine, respectively. The amount of N retained and the N retention from pigs fed corn was 9.5 g/d and 40.9%, respectively. The ATTD of N in corn was 77.1%.

The concentration of ADF was positively correlated ($P < 0.001$) with the concentration of NDF, lignin, cellulose, and particle size, but was negatively correlated ($P < 0.01$) with the concentration of starch (Table 4.9). The concentration of starch was negatively correlated ($P < 0.01$) with the concentration of NDF, lignin, and cellulose. Particle size was positively correlated ($P < 0.01$) with lignin. The concentration of CP was positively correlated ($P < 0.01$) with the concentration of ash. The concentration of lignin and cellulose was negatively correlated ($P < 0.05$) with DE.

The prediction equations for estimating DE and ME are presented in Table 4.10. The optimal models for predicting DE and ME were;

$$DE = -688.58 - 6.11*ash + 0.69*GE + 3.06*NDF - 7.89*lignin + 1.44*bulk\ density - 0.26*particle\ size \quad (1)$$

ME = –784.30 – 7.88*ash + 0.67*GE + 5.48*NDF – 6.80*lignin + 2.22*starch – 0.48*particle size (2)

All models had $R^2 \geq 0.74$.

DISCUSSION

Composition of Experimental Ingredients

Distillers dried grains with solubles are utilized in swine diets because they are relatively high in AA and energy (Stein and Shurson, 2009). When DDGS undergoes the drying process, the high temperature and concentration of moisture makes DDGS susceptible to the Maillard reaction, which can lead to reduced AA concentration and digestibility. Especially, Lys concentration and digestibility may be reduced as a result of the Maillard reaction (Pahm et al., 2008; Almeida et al., 2013). It is recommended that DDGS be used in swine diets only if the Lys:CP ratio is greater than 2.80% (Stein, 2007) because a Lys:CP ratio less than 2.80% indicates that the DDGS has been heat damaged. The average Lys:CP ratio was 3.22% and ranged from 2.87 to 3.67% indicating that all sources of DDGS used in this experiment were not heat damaged. The average concentration of CP and all AA was in agreement with published values (Pedersen et al., 2007; Jacela et al., 2011). The average concentration of ash was greater than reported values (Jacela et al., 2011; Kim et al., 2012a), and among DDGS sources used in this experiment, there was a greater degree of variability (CV = 12.79%) in the concentration of ash compared with DM and CP.

Conventional DDGS contains > 10% fat (NRC, 2012); however, in the past few years, ethanol producers have been centrifuging solubles to extract oil to sell to the biodiesel industry

(Winkler-Moser and Breyer, 2011; Kerr et al., 2013). The resulting DDGS typically contains 6 to 9% fat (NRC, 2012). The average AEE in the 23 sources of DDGS used in this experiment was 7.9% with a range from 5.3 to 10.6%. This observation indicates that oil was extracted from the solubles in the production of some of the DDGS sources. Three of the 23 sources of DDGS had greater than 10% AEE, which indicates that those sources of DDGS had no oil extracted. However, the remaining 20 sources of DDGS contained less than 10% AEE, which indicates that oil may have been extracted during centrifugation. The wide range in AEE among the sources of DDGS used in this experiment indicates that not all ethanol plants are extracting oil and the amount of oil extracted and the extraction method may vary among plants. The concentration of starch in DDGS was on average 1.33%, which is less than published values (Stein et al., 2006; Pedersen et al., 2007; Gutierrez et al., 2014). The concentration of starch in DDGS ranged from not detectable to 6.60% (CV = 126.56%), which indicates that there is variability in the efficiency of starch fermentation among ethanol plants. However, it appears that some plants are very efficient in converting starch to ethanol.

The average GE in the 23 sources of DDGS was less than published data (Pedersen et al., 2007; Kim et al., 2012a; NRC, 2012). The average concentration of ADF in DDGS was above the concentrations reported by Pedersen et al. (2007) and Kim et al. (2012a), but was less than the concentration of ADF in DDGS reported by Jacela et al. (2011). The average concentration of NDF in DDGS was slightly greater than the range in concentrations of NDF in DDGS reported by Pedersen et al. (2007), but was less than the range reported by Kim et al. (2012a), and less than the NDF in DDGS reported by Jacela et al. (2011). The average concentration of lignin in DDGS was greater than the range of concentrations of lignin reported by Anderson et al. (2012). There was a greater variability (CV = 34.74%) in the concentration of lignin compared with the concentration of ADF and NDF.

The range in DDGS bulk density agree with the range in bulk density reported by Anderson et al. (2012). The range in DDGS particle size agreed with published values (Anderson et al., 2012; Kerr et al., 2013). Both Anderson et al. (2012) and Kerr et al. (2013) reported that there is a wide range in DDGS bulk density and particle size, which is consistent with observations in this experiment. The average concentration of Ca, Na, Mg, and Mn in DDGS were less than values reported by NRC (2012), but the average concentration of P, K, S, Zn, Se, and Cu were greater than reported values (NRC, 2012). The range in concentrations of S from 0.37 to 1.20% is in agreement with reported data (Kerr et al., 2008; Kim et al., 2012b) and indicates that some ethanol plants use sulfuric acid to control the fermentation process. The nutrient composition of corn was in agreement with the values reported by NRC (2012), except for the concentrations of ADF, lignin, starch, and Cu, which were all greater than values reported by NRC (2012).

Energy Concentration and Total Tract Digestibility

The DE and ME of corn were 3,842 and 3,673 of kcal/kg DM, which is in agreement with published values (NRC, 2012), but is slightly less than values reported by Pedersen et al. (2007). However, the corn used in this present experiment contained more ADF and lignin than in previous experiments and had a particle size of 885 mμ, which results in lower values for DE and ME than if the particle size is less (Wondra et al., 1995; Rojas and Stein, 2013). The DE and ME in the corn used in this experiment are also greater than the values reported by Liu et al. (2012a) who also used corn with a particle size above 800 mμ. The ATTD of GE in corn was slightly less than reported values (Pedersen et al., 2007; Stein et al., 2009; Kerr et al., 2013). The

ATTD of N in corn was slightly less than reported values (Pedersen et al., 2007; Liu et al., 2012; Kerr et al., 2013).

The average DE and ME in DDGS were less then values reported by Pedersen et al. (2007), Andersen et al. (2012), and Liu et al. (2012), but the DE in DDGS was in agreement with values reported by Kerr et al. (2013). The DE and ME in DDGS were greater than values for DE and ME in de-oiled DDGS (Jacela et al., 2011). These observations are likely a result of the reduced AEE in the DDGS used in this experiment compared with that used in previous experiments with conventional DDGS. There was greater variability in the concentration of ME than in the concentration of DE as indicated by the greater SEM. For every 25 μm decrease in the particle size of DDGS, ME is increased by 13.46 kcal/kg DM (Liu et al., 2012). The variability in DDGS particle size in this experiment may be contributing to the variability in ME. The average ATTD of GE (68.9%) in DDGS was in agreement with the range of ATTD of GE in DDGS reported by Stein et al. (2006), but less than the range of ATTD of GE reported by Kerr et al. (2013) and Stein et al. (2009). The N retained in pigs fed corn was slightly greater than the value reported by Pedersen et al. (2007), however, the concentration of CP in corn used in this experiment was greater than the CP in corn used in Pedersen et al. (2007), which may account for this difference. The N retained from pigs fed DDGS was in agreement with reported values (Pedersen et al., 2007). The average ATTD of N (81.2%) in DDGS was in agreement with published values (Pedersen et al., 2007; Stein et al., 2009; Liu et al., 2012; Kerr et al., 2013).

Fiber was the main chemical component that contributed to the prediction of DE and ME, which is similar to previous prediction equations for DE and ME in DDGS (Pedersen et al., 2007; Anderson et al., 2012). Acid hydrolyzed ether extract was not a component included in the prediction equations for DE and ME in DDGS used in this experiment. This is consistent with published prediction equations for DE and ME in DDGS (Pedersen et al., 2007; Anderson et al., 2012). It is possible that fiber contributes more to the prediction of DE and ME in DDGS compared with EE because there is greater concentration of fiber in DDGS compared with EE (Kerr et al., 2013). Bulk density and particle size were included in the prediction of DE in DDGS, which is consistent with the prediction of DE in DDGS reported by Kerr et al. (2013). However, in the prediction of ME of DDGS, only particle size was included and not bulk density. It is likely that the wide range in particle size in the 23 sources of DDGS used in this experiment (266 to 930 μm) contributed to the variability of ME that was observed. Bulk density and particle size in DDGS can be influenced by the amount of solubles added to wet grains prior to drying (Kingsly et al., 2010), and the amount of solubles added to wet grains may be another source of variability in composition of DDGS. In this experiment, the prediction equation for DE and ME in DDGS was significant, however when these equations are used to predict DE and ME in DDGS, they are only moderately accurate as indicated by the R^2 values of 0.78 and 0.74.

In conclusion, the DDGS procured from ethanol plants in IL and surrounding states varied in nutrient composition, nutrient digestibility, and DE and ME concentration. The variability may have been caused by the amount of solubles added to wet grains prior to drying or the centrifugation of solubles for oil extraction. In this experiment, we were able to generate moderately accurate prediction equations for DE and ME in DDGS; however, more research should be conducted to determine high accuracy equations for DE and ME in DDGS.

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TABLES

Table 4.1. Ingredient composition (%) of experimental diets, as-fed basis

Item	Corn Diet	DDGS[1] Diets
Corn	97.80	57.80
DDGS	-	40.00
Limestone	1.35	1.35
Monocalcium phosphate	0.15	0.15
Salt	0.40	0.40
Vitamin-mineral premix[2]	0.30	0.30

[1]DDGS = distillers dried grains with solubles.

[2]Provided the following per kg of complete diet: vitamin A as retinyl acetate, 11,136 IU; vitamin D3 as cholecalciferol, 2,208 IU; vitamin E as DL-alpha tocopheryl acetate, 66 IU; vitamin K as menadione dimethylprimidinol bisulfite, 1.42 mg; thiamin as thiamine mononitrate, 0.24 mg; riboflavin, 6.59 mg; pyridoxine as pyridoxine hydrochloride, 0.24 mg; vitamin B12, 0.03 mg; D-pantothenic acid as D-calcium pantothenate, 23.5 mg; niacin, 44.1 mg; folic acid, 1.59 mg; biotin, 0.44 mg; Cu as copper sulfate and copper chloride, 20 mg; Fe as ferrous sulfate, 126 mg; I as ethylenediamine dihydriodide, 1.26 mg; Mn as manganese sulfate, 60.2 mg; Se as sodium selenite and selenium yeast, 0.3 mg; and Zn as zinc sulfate, 125.1 mg

Table 4.2. Analyzed nutrient composition of experimental diets, as-fed basis

		DDGS[1]				
Item	Corn	Mean[2]	Low	High	SD	CV
DM, %	86.35	88.55	84.14	90.76	2.28	2.27
Ash, %	3.84	5.18	4.29	6.28	0.47	8.98
CP, %	8.23	17.18	14.95	18.78	0.89	5.21
ADF, %	3.34	7.11	5.14	9.17	1.00	14.01
NDF, %	8.45	16.38	14.31	18.97	1.15	7.02
GE, kcal/kg	3,857	4,069	3,999	4,237	52.41	1.29

[1]DDGS = distillers dried grains with solubles.

[2]Represents the mean of diets containing each of 23 sources of DDGS.

Table 4.3. Proximate analysis, gross energy, bulk density, and particle size of corn and 23 sources of distillers dried grains with solubles (DDGS), as-fed basis

		DDGS				
Item	Corn	Mean[1]	Low	High	SD	CV
DM, %	88.58	90.36	87.93	93.29	1.09	1.20
Ash, %	1.28	5.98	4.86	7.42	0.76	12.71
CP, %	8.57	29.94	24.58	32.21	1.76	5.89
AEE[2], %	3.79	7.92	5.25	10.58	1.29	16.26
GE, kcal/kg	3,938	4,556	4,335	4,934	135.21	2.97
Bulk density, g/L	611	482	368	548	42.70	8.86
Particle size, μm	885	589	266	930	177.58	30.13

[1]Represents the mean of 23 sources of DDGS.

[2]AEE = acid hydrolyzed ether extract.

Table 4.4. The concentration of AA in corn and 23 sources of distillers dried grains with solubles (DDGS), as-fed basis

		DDGS				
Item	Corn	Mean[1]	Low	High	SD	CV
Indispensable AA, %						
Arg	0.41	1.28	1.10	1.41	0.09	7.27
His	0.25	0.80	0.72	0.85	0.04	5.20
Ile	0.29	1.14	0.97	1.26	0.07	6.50
Leu	1.00	3.39	2.91	4.00	0.26	7.67
Lys	0.31	0.96	0.74	1.08	0.09	9.00
Met	0.17	0.55	0.44	0.60	0.04	8.04
Phe	0.41	1.46	1.27	1.68	0.10	6.95
Thr	0.31	1.11	0.95	1.21	0.07	5.90
Trp	0.06	0.18	0.15	0.21	0.02	9.80
Val	0.39	1.41	1.24	1.55	0.09	6.22
Total	3.60	12.28	10.51	13.68	0.78	6.33
Dispensable AA, %						
Ala	0.62	1.99	1.70	2.28	0.14	7.17
Asp	0.56	1.80	1.54	2.02	0.11	6.39
Cys	0.18	0.53	0.45	0.60	0.04	8.17
Glu	1.52	4.00	3.17	5.11	0.44	11.02
Gly	0.35	1.22	0.95	1.35	0.10	7.96
Pro	0.73	2.19	1.83	2.61	0.17	7.55
Ser	0.40	1.32	1.10	1.56	0.09	7.20
Total	3.96	13.11	10.74	15.39	1.03	7.82
Total, all AA	7.17	25.38	21.25	29.07	1.72	6.79
Lys:CP ratio,[2] %	3.62	3.22	2.87	3.67	0.21	6.41

[1]Represents the mean of 23 sources of DDGS.

[2]The Lys:CP ratio was calculated by expressing the concentration of Lys in each sample as a percentage of the concentration of CP (Stein et al., 2009).

Table 4.5. Carbohydrate concentration in corn and 23 sources of distillers dried grains with solubles (DDGS), as-fed basis

		DDGS				
Item	Corn	Mean[1]	Low	High	SD	CV
ADF, %	4.31	13.58	8.38	19.08	2.45	18.01
NDF, %	9.08	28.42	23.42	33.26	2.87	10.09
Lignin, %	1.07	3.92	0.96	7.15	1.36	34.74
Hemicellulose[2], %	4.77	14.84	10.19	19.18	2.29	15.43
Cellulose[3], %	3.24	9.66	6.22	11.93	1.38	14.28
Starch, %	66.83	1.33	ND[4]	6.60	1.68	126.56

[1]Represents the mean of 23 sources of DDGS.

[2]Calculated as hemicellulose = NDF – ADF (NRC, 2012).

[3]Calculated as cellulose = ADF – lignin (NRC, 2012).

[4]ND = not detectable.

Table 4.6. Mineral composition of corn and 23 sources of distillers dried grains with solubles (DDGS), as-fed basis

		DDGS				
Item	Corn	Mean[1]	Low	High	SD	CV
Macrominerals, %						
Calcium	0.01	0.04	0.01	0.10	0.02	64.56
Phosphorous	0.27	0.79	0.63	0.90	0.07	8.53
Sodium	ND[2]	0.20	0.08	0.41	0.08	41.19
Potassium	0.34	1.05	0.93	1.19	0.07	7.10
Magnesium	0.10	0.29	0.23	0.34	0.03	10.10
Sulfur	0.12	0.70	0.37	1.20	0.21	29.38
Microminerals, mg/kg						
Iron	18.4	80.10	43.50	113.60	16.43	20.51
Zinc	20.5	64.29	44.30	99.30	10.96	17.04
Selenium	4.00	4.33	4.00	5.00	0.58	13.32
Molybdenum	0.30	0.84	0.30	1.70	0.35	41.97
Manganese	4.70	15.74	11.20	31.00	4.09	26.01
Copper	1.70	6.65	5.00	11.00	1.58	23.74

[1]Represents the mean of 23 sources of DDGS.

[2]ND = not detectable.

Table 4.7. Concentrations of DE and ME, daily N balance, and apparent total tract digestibility (ATTD) of GE, N, DM, and OM in experimental diets containing corn or distillers dried grains with solubles (DDGS), as-fed basis

		DDGS				
Item	Corn	Mean[1]	Low	High	SEM[2]	*P*-value[2]
DE, kcal/kg	3,329	3,223	3,096	3,342	29.55	<0.01
ME, kcal/kg	3,182	3,027	2,914	3,173	38.17	<0.01
N intake, g/d	25.2	53.0	46.4	57.8	5.14	<0.01
N in feces, g/d	5.8	10.3	9.1	12.1	0.87	<0.01
N in urine, g/d	8.6	21.0	15.0	26.0	3.99	0.03
N absorbed, g/d	19.4	42.7	35.1	47.4	4.40	<0.01
N retained, g/d	9.3	21.9	16.6	25.4	2.84	<0.01
N retention[3], %	40.9	42.2	32.2	51.2	4.10	<0.01
ATTD of GE, %	86.3	79.2	77.4	81.4	0.73	<0.01
ATTD of N, %	77.1	80.1	75.0	83.1	0.98	<0.01
ATTD of DM, %	88.6	80.9	78.6	82.7	0.64	<0.01
ATTD of OM, %	89.7	81.7	79.1	83.4	0.67	<0.01

[1]Represents the mean of 23 sources of DDGS.

[2]Comparison of the 23 diets containing DDGS.

[3]Calculated as N retention = (N retained/N intake) × 100.

Table 4.8. Concentration of DE and ME, daily N balance, and apparently total tract digestibility (ATTD) of GE and N in corn and distillers dried grains with solubles (DDGS), as-fed basis

		DDGS				
Item	Corn	Mean[1]	Low	High	SEM[2]	*P*-value[2]
DE, kcal/kg	3,403	3,139	2,822	3,437	73.88	<0.01
DE, kcal/kg DM	3,842	3,474	3,145	3,786	81.57	<0.01
ME, kcal/kg	3,254	2,867	2,584	3,230	93.60	<0.01
ME, kcal/kg DM	3,673	3,173	2,880	3,598	103.53	<0.01
N intake, g/d	25.8	38.1	31.5	42.9	5.14	<0.01
N in feces, g/d	5.9	6.9	5.6	8.7	0.87	<0.01
N in urine, g/d	8.8	14.1	8.0	18.5	3.95	0.01
N absorbed, g/d	19.9	31.1	23.7	36.0	3.11	<0.01
N retained, g/d	9.5	17.1	12.3	21.2	2.88	<0.01
N retention[3], %	40.9	44.5	32.4	58.5	4.19	<0.01
ATTD of GE, %	86.4	68.9	62.6	75.4	1.62	<0.01
ATTD of N, %	77.1	81.2	74.0	85.2	1.42	<0.01

[1]Represents the mean of 23 sources of DDGS.

[2]Comparison of the 23 sources of DDGS.

[3]Calculated as N retention = (N retained/N intake) × 100.

Table 4.9. Correlation coefficients (r) among and between chemical composition, physical characteristics, and DE and ME in distillers dried grains with solubles (DDGS)[1]

	Correlation coefficient, r												
Item	Ash	CP	AEE[2]	ADF	NDF	Lignin	Hemi-cellulose	Cellulose	Starch	BD[3]	Particle size	DE	ME
Ash		0.54**	-0.31	-0.04	-0.05	-0.05	-0.04	-0.05	0.08	0.30	-0.27	-0.28	-0.32
CP			-0.13	-0.07	0.11	0.05	0.21	-0.17	-0.27	0.44*	-0.23	-0.04	-0.15
AEE				0.02	-0.30	0.17	-0.31	-0.09	0.31	0.32	0.34	0.20	0.15
ADF					0.62***	0.88***	-0.25	0.90***	-0.68**	-0.24	0.63**	-0.50*	-0.32
NDF						0.48*	0.60**	0.61**	-0.70**	-0.35	0.39	-0.19	-0.07
Lignin							-0.29	0.60**	-0.61**	-0.05	0.54*	-0.43*	-0.32
Hemicellulose								-0.18	0.04	-0.20	-0.15	0.28	0.23
Cellulose									-0.61**	-0.38	0.59**	-0.47*	-0.25
Starch										0.16	-0.44	0.27	0.18
BD											-0.13	0.30	0.16
Particle size												-0.35	-0.29

*P < 0.05, **P < 0.01, ***P < 0.001.

[1]A total of 23 sources of DDGS were used.

[2]AEE = acid hydrolyzed ether extract.

[3]BD = bulk density.

Table 4.10. Prediction equations for estimating the concentration of DE and ME in distillers dried grains with solubles (DDGS) fed to growing pigs[1,2]

Equation	C(p)	AIC	RMSE	R^2	*P*-value
DE = –1152.25 – 4.08*ash + 0.77*GE + 2.81*NDF – 9.81*lignin + 1.27*bulk density	2.25	161.66	101.43	0.76	0.013
DE = –688.58 – 6.11*ash + 0.69*GE + 3.06*NDF – 7.89*lignin + 1.44*bulk density – 0.26*particle size	3.58	162.00	101.31	0.78	0.011
ME = –784.30 – 7.88*ash + 0.67*GE + 5.48*NDF – 6.80*lignin + 2.22*starch – 0.48*particle size	3.54	171.09	132.36	0.74	0.017

[1]C(p) = criterion used to determine which model maximizes explained variability (R^2) with the least amount of variables. Models whose C(p) was close to p, where p = number of variables in model + 1, were chosen as candidate models. The optimum model is the prediction equation with the lowest Akaike Information Criterion (AIC), which is a measure of fit, and root mean square error (RMSE), which measures precision.

[2]Units for DE and ME are kcal/kg DM; units for chemical composition are % of DM, bulk density is g/L, and particle size is μm.

CHAPTER 5

CONCLUSIONS

The focus of this research was to investigate sources of variability in composition and digestibility of nutrients in distillers dried grains with solubles (**DDGS**). The purpose of the experiments was to compare the standardized ileal digestibility (**SID**) of AA by growing pigs in European DDGS produced from wheat, maize, or wheat-maize mixtures and to determine if the concentrations of DE and ME in maize DDGS produced in and around IL vary among plants.

Results of the first experiment indicate that wheat DDGS from 2011 and wheat DDGS from 2012 did not have different nutrient composition or SID of AA and maize DDGS had greater SID of AA compared with both sources of wheat DDGS. For nutrient composition and SID of AA, the DDGS derived from blends of wheat and maize were intermediate between maize DDGS and wheat DDGS. These results indicate that the nutrient composition and SID of AA of DDGS can be influence by the composition of the starting feedstock.

Results of the second experiment indicate that composition and digestibility of nutrients and DE and ME concentration in DDGS vary among 23 sources of DDGS from ethanol plants in IL or surrounding states. Acid hydrolyzed ether extract was less than 10% in some sources of DDGS, which indicated that solubles were being centrifuged for oil extraction. Prediction equations for DE and ME in DDGS were generated, but the accuracy with which DE and ME could be predicted was only moderate.

Overall, starting feedstock composition can influence the nutrient composition and digestibility in DDGS. Processing procedures and technologies can cause variation of nutrient digestibility and DE and ME concentrations in DDGS.