# THE EFFECTS OF DDGS INCLUSION ON PELLET QUALITY AND PELLETING PERFORMANCE

by

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# Abstract

Three experiments were conducted to evaluate the effects of distillers dried grains with solubles (DDGS) on pellet quality and pellet mill performance in pelleted swine diets. The experiments were completed at the Feed Processing Research Center in the Department of Grain Science at Kansas State University. In all experiments, pellet durability index (PDI), electrical energy consumption, production rate, and bulk density served as the response criteria. In Exp. 1, DDGS were substituted on an equal weight basis for corn, with substitution levels of 10%, 20%, 30%, and 40%. The diet was not adjusted to maintain equal nutrient levels across the treatments. There were no observed significant differences in pellet quality across all levels of DDGS substitution. Both production rate and bulk density were significantly lowered as DDGS level increased. In Exp. 2, diets were formulated to contain the same levels of DDGS, but all ingredients were allowed to vary to retain nutritionally similar diets. In this case energy consumption showed no significant differences among treatments, while pellet quality, throughput, and bulk density were all negatively affected by increasing levels of DDGS. In Exp. 3, the effect of incorporating pelleted and reground DDGS was evaluated. The levels of DDGS evaluated were 10%, 20%, and 30%, using the same diets as Exp. 2. These diets were then pelleted and compared to a control diet with no added DDGS and to diets with unprocessed DDGS added at the same levels. At levels above 10% the diets containing unprocessed DDGS had significantly lower pellet quality than the control, while the diets containing pelleted and reground DDGS showed no significant difference from the control at any level. Significant effects were also observed for production rate, energy consumption, and bulk density. In conclusion, the use of standard DDGS in pelleted feeds is feasible, and although pellet quality may be significantly lower for feeds containing DDGS, the practical value is likely not affected. Furthermore, the data demonstrates some benefits of using DDGS that have been pelleted and reground.

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# Introduction

Distillers dried grains with solubles (DDGS) is not a new ingredient in the feed industry, and has been used in animal rations for decades. Historically, DDGS have been viewed as a by-product, with little or no value, and little attention has been given to marketing. In the past, because of the moderate quantities produced, DDGS were sold locally, mostly to feed mills and beef and dairy cattle operations. However, the recent and dramatic rise in ethanol production resulted in the production of more DDGS than had ever been expected. With an increased DDGS supply local markets quickly became saturated, and the use of DDGS became attractive to a wider consumer base as a relatively low-cost ingredient to replace corn and soybean meal.

A larger supply and more widespread use meant increased transportation requirements, which had not been an issue for DDGS in the past, and problems began to surface. Because of a low bulk density, typically 30-35 pounds per cubic foot, DDGS may fill transportation volume, whether in a rail car or a bulk truck, before realizing the maximum allowable weight, thus increasing the commercial shipping cost. A second problem encountered was poor flowability, as bridging causes problems in unloading DDGS at the feed mill or transfer station, and in the storage of the DDGS in bins. This requires extra labor to manually remove the DDGS from storage units, resulting in additional cost.

Nutritionally, DDGS can vary significantly from one ethanol plant to another based on the qualities of the grain used and processing methods specific to each plant. Corn is the typical feedstock, and the resultant DDGS are 25 to 30% crude protein, 8 to 10% fat, and have calcium and phosphorus levels approximately 3 times those found in corn. DDGS are used in feed rations as a source of inexpensive protein and energy, often as substitutes for corn and soybean meal, both of which have increased in price because of the demand for corn by the ethanol industry.

Though there have been numerous studies investigating the nutritional effects of utilizing DDGS in animal feed, very little information is available on how DDGS will affect pelleting ability, pelleting efficiency, and pellet quality. At this time there are conflicting opinions throughout industry and academia alike, with some believing that DDGS pose few problems to processing, while others believe that the inclusion of DDGS in a diet will make the diet unable to be pelleted at all. Furthermore, the practice of pelleting pure DDGS to improve handling during shipping and storage has been a topic of interest to researchers and the feed industry alike, and little information is available on how pelleted DDGS will affect further feed processing. If DDGS cannot be used effectively in pelleted feed, then the use as a feed ingredient is extremely limited. The experiments conducted for this thesis take into consideration these feed processing concerns, with a goal of providing data on the ability to produce high quality pelleted feeds and the effects of DDGS on pellet mill performance.

# Literature Review

## Distillers Grains Background and Growth

Bio-based fuel ethanol is the product of fermentation of cereal grains, and is used as a replacement for gasoline as a source of energy to power vehicles and motorized equipment. The interest in producing fuel ethanol has increased rapidly in just the last decade, but the reasons are not new. The oil embargo of the mid 1970's was one of the earliest signs to U.S. consumers that there was a need for energy independence. Since that time it has been clear that, without control over fuel prices and availability, the economy and security of the U.S. is partially out of domestic hands. Thirty years after the embargo, in 2005, the Energy Policy Act (commonly referred to as the Renewable Fuels Act) was passed. This created the Renewable Fuels Standard, guidelines which dictate the amount of biofuels that must be produced annually, and which has been updated as recently as 2007 to provide requirements through 2022 (Renewable Fuels Association).

Government subsidies paid to ethanol companies have been responsible for an amazingly quick growth of the industry. To keep up with demand, corn producers have started planting more acres to corn, sacrificing the production of other crops. And though concerns have been widely voiced about the sustainability of the ethanol industry, and competition for corn has pushed prices higher than ever before, the ethanol industry has continued to grow. The renewable fuels association estimates that there are currently 176 operating ethanol biorefineries in the U.S., which collectively produce approximately 10,735.4 million gallons of ethanol per year. In addition, there are currently 27 biorefineries under construction, which will add an additional 2,306 million gallons to the annual production capacity.

The production of fuel ethanol, like many industrial processes, generates by-products, in this case carbon dioxide and distillers grains. Distillers grains, often in the form of distillers dried grains with solubles (DDGS) are of great interest to the animal feed industry. DDGS are defined by the Association of American Feed Control Officials (AAFCO) as: the product obtained after the removal of ethyl alcohol by distillation from the yeast fermentation of a grain or a grain mixture by condensing and drying at least ¾ of the solids of the resultant whole stillage by methods employed in the grain distilling industry. And while DDGS have been produced for over 50 years, and have been used sparingly as a feed ingredient for decades, it is only recently that DDGS have become widely used. Expansion of ethanol production has resulted in DDGS saturating the traditional markets, and consequently DDGS have become extensively available at a cheap price, allowing them to price into rations where least cost formulation is used. In addition to increased production, improvements in the process and decreasing ethanol margins have led to producers taking steps to add value to DDGS. DDGS with improved nutritional values, and an increase in DDGS nutrition related research (largely due to a desire by the food production industry to lower feed costs), has allowed feed producers to increase their use of DDGS.

In 2006 ethanol biorefineries produced approximately 14 million tons of DDG (Sims, 2007). As a general rule of thumb, for every 2.7 gallons of ethanol, 18 pounds of distillers grains are produced (Feed International, 2007). While considered to be one product, different ethanol production facilities do not necessarily produce the same DDGS. Different methods of ethanol production produce different amounts and types of DDGS per gallon of ethanol, and different feed stocks, such as sorghum and barley, produce different amounts of ethanol and different DDGS compared to corn. New generation ethanol plants, typically built after 1990, have improved fermentation procedures leading to increased starch removal and ethanol yield. Also, development of technologies such as up-front fractionation, in which the bran, germ, and endosperm of corn are separated before fermentation, and efforts by companies such as Poet Nutrition, which manufactures Dakota Gold® brand DDGS, have yielded high quality and lower-variability DDGS, two qualities that were previously difficult to find. Highly fermentable starch hybrids, which are being created by seed companies especially for the use in ethanol production and may yield three to five percent more ethanol per bushel of corn (NCGA, 2006), will certainly change the balance of ethanol versus DDGS production.

Traditional feedstuffs, such as corn and soybean meal, currently have high costs, due in part to the increased demand for corn by the ethanol industry. With many companies using least-cost formulation methods, and all companies trying to keep costs as low as possible, the low cost of DDGS relative to corn and soybean meal makes for an attractive replacement for both ingredients. For example, according to the September 15, 2008 issue of Feedstuffs, DDGS prices at the Kansas City market were listed at $160 per ton. At that time corn prices were $5.07 per bushel (or roughly $180 per ton), and soybean meal prices were $363 per ton. It is clear that the savings to a feed processor by using DDGS to replace corn and soybean meal could be substantial as these two ingredients often make up the majority of swine and poultry diets.

## Feeding DDGS

A potential complication in the use of DDGS is the fact that DDGS are unique in nutritional composition. This can make formulation difficult for nutritionists as DDGS cannot be simply substituted without also varying protein, energy, mineral, and specific amino acid levels. Adding to this complication is the fact that different factors can lead to very different DDGS from a nutritional standpoint. According to a study conducted by Spiehs et al. (2002), most of the variation in the nutrient content of DDGS comes from the crop used, percent of dried solubles added back to DDGS, and the completeness or duration of the fermentation process. In general however, nutrient variation levels between plants considered was low in respect to dry matter (DM), digestible energy (DE), and metabolizable energy (ME), with coefficients of variation (CVs) of less than 5%, and also in respect to crude protein, fat, and fiber, with CVs of less than 10%. While amino acids generally had CVs of less than 10% among plants, lysine and methionine levels had relatively high variation (CV of 17.3% and 13.6% respectively). Also, mineral levels were highly variable among sources. While these variations can be accounted for at the feed mill by adding minerals and synthetic amino acids, the importance of knowing the makeup of the DDGS source is evident.

While DDGS can be very different among sources, there are some general consistencies that affect the nutritional value. Because corn is typically the primary grain used in ethanol production, DDGS share the inferior amino acid profile (Spiehs et al. 2002). An improper amino acid balance in relation to overall crude protein will lead to inefficient energy usage, and thus decreased growth performance, and so the use of synthetic amino acids and the control of crude protein levels are necessary with the use of DDGS. Crude fiber values are relatively high with DDGS at approximately 7-8%, as are crude fat values at 9-10% (Shurson et al. 2004). This high crude fat level means that DDGS have a similar energy value in comparison to corn, thus increasing its attractiveness as a component replacement for corn in diet formulation. DDGS also provide an interesting benefit in the form of phosphorus availability. While corn is low in overall (0.28%) and biologically available (14%) phosphorus, the phosphorus concentration in new generation DDGS is approximately 0.89% with an increased bioavailability of 90%, due to changes occurring during the fermentation process (Shurson et al. 2004).

A number of studies have been conducted that demonstrate the possibilities of using DDGS in swine diets. Many of these studies have been completed fairly recently and focus on how an increasing level of DDGS affects feed intake and growth performance. Whitney and Shurson (2004) describe the effects of increasing DDGS on the growth performance of nursery pigs. In one experiment, results showed that increasing DDGS from 0% to 25% had no significant effect on growth rate ($p>0.10$) during phase 2 and 3 periods. There were also no differences in average daily feed intake (ADFI) or gain to feed ratio (G/F). In a second experiment, increasing DDGS during phase 2 decreased ADFI ($p<0.05$) and average daily gain (ADG) ($p<0.09$), but had no effect on G/F. In phase 3 however, no effects on ADG, G/F, or ending body weight were observed, with overall results for phase 2 and 3 feeding showing no treatment effects on ADG or G/F ($p>0.10$), and a linear decrease in voluntary feed intake with increasing DDGS ($p<0.09$). Final conclusions from this study state that DDGS may be included at levels up to 25% in phase 2 and 3 diets without affecting growth performance or feed intake, but that for young or small pigs some acclimation period may be warranted before including high levels of DDGS in the diet.

Studies have also been conducted with growing and finishing pigs, following similar ideas of increasing levels of DDGS in the diet. Linneen et al.(2008) reported a linear decrease in ADG and ADFI ($p=0.09$ and $p<0.05$, respectively), and no effect on G/F as DDGS in the diet increased from 0% to 30% during a 56-day growth study. The authors indicated that the most notable decreases were seen at levels above 10%. In a second experiment, pigs were fed diets with increasing levels of DDGS from 0% to 20% over a 78-day growth period. During this period there was a linear decrease in ADG and ADFI ($p \leq 0.04$), and an increase in G/F ($p=0.06$) as the level of DDGS increased. There were also negative effects on carcass weight and percentage yield with increasing DDGS level. In this second experiment the authors noted the greatest differences between pigs fed 15% and 20% DDGS. The authors concluded that levels of 10% to 15% of DDGS can be included in the diet without compromising growth performance.

Similar results were found by Wahlstrom et al.(1970) in experiments to determine the effect of increasing levels of DDGS (from 0% to 20%) in the diet on gain, feed consumption, feed conversion, and nutrient digestibility, and also to examine the effects of lysine supplementation. Results showed little or no differences in ADG or ADFI as DDGS level increased, but there was a negative impact on feed conversion at a level of 20% DDGS. Also, there was a significant decrease in apparent digestibility of protein, nitrogen-free extract (NFE), and DM at the 20% level. Supplementation of lysine to the diets did not affect performance, but did improve G/F for the pigs fed the 20% level. Work done by Whitney et al. (2006) shows a reduced ADG ($p<0.05$) in pigs fed 20% or 30% DDGS compared with pigs fed 0% and 10%, and a decrease in G/F with the 30% DDGS treatment ($p<0.05$). ADFI was unaffected by dietary treatment, and the researchers concluded that less than 20% DDGS should be included in the diet for optimal performance of grow-finish pigs.

Other researchers have shown that up to 30% DDGS may be included in the diet for growing pigs. In one case, there was no negative effect on ADG or ADFI as the level of DDGS increased, but there was an increase in G/F ($p<0.05$) for the pigs fed the 20% and 30% inclusion rates compared to the 0% DDGS treatment (DeDecker et al. 2005). A study conducted by Cook et al. (2005) also concluded that up to 30% DDGS may be included without affecting growth performance or carcass lean percentage. In addition, this study found that there was a linear decrease in mortality as DDGS level was increased ($p<0.05$), which may possibly indicate a value in feeding DDGS to health challenged swine populations.

In addition to growth performance, studies have also been conducted to examine how the level of DDGS might affect feed preference. An experiment of this type is concerned both with overall palatability of the diet as well as ADFI. Hastad et al. (2005) conducted a series of experiments to determine if growing pigs showed preference regarding diets containing different sources and increasing levels of DDGS. Investigating how DDGS source might affect feed intake, pigs were fed diets with and without DDGS, with there being two treatments containing 30% DDGS from two separate sources, one from an old generation ethanol plant (built before 1990) and one from a new generation plant (built after 1990). Overall, the researchers found that feed intake was lower ($p<0.01$) for each of the diets containing DDGS compared to the control diet. In a second experiment, diets were fed containing 0%, 10%, 20%, or 30% DDGS, and there was a linear decrease ($p<0.01$) in ADFI as the level of DDGS in the diet increased. These experiments demonstrate a preference for feeds not containing DDGS, but it should be noted that the experimental design allowed pigs to choose between feeders containing different diets, a choice that would not be available in commercial feeding.

Experiments have also been conducted to determine the levels of DDGS use possible in broiler feeds. Wang et al. (2007a) conducted an experiment to determine how different levels of DDGS would affect growth performance of broilers over a 49-day growing period. Diets were formulated to contain 0, 5, 10, 15, 20, and 25% DDGS. Starter diets were fed as crumbles while grower and finisher diets were fed as pellets. No significant effects were observed on body weight as DDGS level increased, but feed conversion suffered for birds fed the 25% DDGS diet compared to those fed the control. Overall, the authors found that DDGS may be used in broiler diets at levels up to 20% without affecting performance, but there may be negative effects on carcass characteristics and yield.  Similar results were found by Lumpkins et al. (2004) where no difference in growth performance was found among chicks fed 0 or 15% DDGS, and in a second experiment only a level of 18% (among 0, 6, 12, and 18% DDGS) caused a decrease in gain or feed performance.  In this case the authors concluded that 6% DDGS can be fed during the starter period, and 12 to 15% through grow and finish feeding.

In general, studies conducted on the use of DDGS in feed have concluded that at least some level of use is possible in most situations.  Differences in DDGS source, which would be caused by ethanol plant location, age, and fermentation technology, and crop variability may explain differences among experiments.  One issue mentioned in most of the studies cited is that while both feed and growth performance are important, final carcass characteristics and yield must be considered from an economic standpoint.  And while the poultry research diets are typically pelleted, the research concerning swine is done using mash diets.

## Handling and Processing DDGS

### *Pelleting*

While the use of DDGS has been shown to be nutritionally viable, and research has and is being conducted on improvements in DDGS handling, one specific question remains: how do DDGS perform in pelleted diets?  This question concerns pellet quality as well as pelleting efficiency, and little to no work has been conducted in this area.  However, a number of feeding studies have been conducted using pelleted diets containing DDGS, and some have reported basic findings regarding pellet quality.

Generally, expectations are that increased DDGS lead to a decrease in pellet quality. Wang et al. (2007a) found that the quality of pellets decreased from a visual standpoint as DDGS were added to the diet at levels of 0, 15, and 30%, with diets containing 30% DDGS pelleting "extremely poorly" with many fines. However, pellet quality was not measured by any method other than visual observation, which leaves questions about overall pellet quality and durability. These results correspond with findings from Min et al. (2008), in which an increased level of fines was produced as DDGS were added to the diets in the starter, grower, and finisher phases, again at levels of 0, 15, and 30%. Starter diets were pelleted using a 2.38 mm (3/32") die while grower and finisher diets were pelleted using a 4.76 mm (3/16") die; no mention of die thickness is made. In this case, percentage fines was measured by sifting pellets over a 2 mm screen for 30 seconds. Fines increased from 1.05 to 12.04% in starter diets, 10.53 to 26.89% in grower diets, and 12.83 to 42.64% in finisher diets. However, as in Wang et al. (2007a), the amount of fat added to the diet as DDGS percentage increased rose significantly in order to retain isocaloric diets. This increase in fat could certainly explain a large amount of the increase in fines. In diets where fat level was kept constant, less variation is seen in the percentage of fines as DDGS level increases (Wang et al, 2008).

While most of the research involving swine diets and the inclusion of DDGS has been done using mash feeding, some studies have been conducted using pelleted diets. Stender et al. (2008) fed diets to finishing pigs that contained 0, 20%, and 40% DDGS. Pellets were evaluated for pellet quality using a tumbling method similar to the method described in ASAE S269.4, which is also known as the KSU pellet durability test. Pellet durability was found to decrease as the level of DDGS increased with durabilities of 78.9, 66.8, and 47.4% for the levels of 0, 20, and 40%, respectively. This decrease is in contrast with the work done by Feoli (2008), which found an increase in pellet quality when adding 30 or 40% DDGS to swine diets. This study used the KSU pellet durability method, and found an increase from 88.5% PDI for the corn-soy control diet to 93.0 and 91.9% PDI with 30% corn and sorghum DDGS, respectively, in nursery diets. An increase from 76.3 to 87.7% PDI was found in grow finish diets when comparing a corn-soy control to a diet containing 40% sorghum DDGS. All diets for this study used a 3.97 mm (5/32") by 22.22 mm (7/8") pellet die (L:D ratio of 5.6:1).

Pellet bulk density is also an important characteristic concerning diets containing DDGS. Lower bulk densities mean less feed can be stored in storage bins at the feed mill or on the farm, and also limits the amount that can be transported by truck between the two. Wang et al. (2007b) found a decrease in bulk density as the percentage of DDGS in the diet increased in pelleted grower diets. However, in pelleted finisher diets, the bulk density increased from the control to the diet containing 15% DDGS, then decreased as the level increased to 20 and 25%. This may have been due to fines or overall pellet quality, neither of which was specifically addressed.

### *Transportation and Storage*

Some of the largest concerns in feeding DDGS come not from the feed performance and pelleting issues, but instead from the handling of DDGS during transportation, storage, and throughout processing. DDGS are known for poor flow characteristics and low bulk density, both issues that contribute to problems in material handling. DDGS tend to bridge up in storage bins as well as in transportation vessels such as trucks or rail cars. Poor bulk density means that less DDGS can be stored in existing bin space and also leads to increases in transportation costs as trucks and rail cars are filled before reaching maximum weight allowance.

Poor flowability becomes a major issue in transporting DDGS. The United States Department of Agriculture (USDA) conducted a survey in 2003 to determine the cost of production of ethanol (USDA, 2005). This survey was conducted at 21 dry-grind ethanol plants, and provided data on DDGS production and shipping among other costs and production figures. Of the plants surveyed, 70% shipped distillers grains as DDGS, as opposed to wet distillers grains (WDG) or modified distillers grains (MDG). Trucks, trains, and barges were used to transport DDGS, with the average distance of travel for trucks being 161 miles with a maximum of 600 miles, and an average distance of 994 miles for trains with a maximum of 3000 miles.

The combination of poor flowability and large shipping distances can create a major problem when unloading DDGS. The long-term vibrations occurring during travel, along with the cohesive properties of DDGS create severe bridging in shipping vessels. This bridging means increased unloading times, and increased labor costs, along with damage to trucks and railcars as force must often be used to remove the DDGS during unloading.

Ganesan et al. (2008) conducted experiments to examine the flow properties of DDGS over a range of soluble levels (10-25%) and moisture content (10-30%). Results show that increased solubles levels inhibit the flow of DDGS and that, dependent on solubles levels, an increase in moisture can increase the flowability of DDGS. This explains typically poor flow characteristics as DDGS are commonly used at levels of approximately 10% moisture. High solubles and moisture levels were found to increase compressibility, which could certainly affect setting up inside storage bins, and DDGS were classified overall as a cohesive material, likely to have cohesive arching issues. With poor flowing materials, a common remedy is the addition of flow agents, but the addition of calcium carbonate, or limestone, which is a typical flow agent used in the feed industry has no positive effect on DDGS, possibly because of a lack of cohesion between the DDGS and the flow agent itself (Ganesan et al. 2006).

Work has also been done to examine the effects of pelleting on flowability of DDGS. Pelleting 100% DDGS has been shown to be possible (AURI, 2005, Wilson and McKinney, 2008), and could be done directly at the ethanol plant prior to shipping. Improvements in bulk density have been noted, along with an increased pellet durability as the ratio of pellet die width to pellet diameter, commonly known as the L:D ratio, is increased (AURI, 2005, Wilson and McKinney, 2008). Increased bulk density would improve cost of shipping as vessels could be loaded closer to maximum weight. Pelleting may also reduce flowability problems inherent with DDGS by creating a more uniform product and by reducing surface area, which would limit friction and cohesion.

## Pelleting

### *Processing*

The pelleting of animal feed can improve logistics along the feed system. Pelleted diets have an increased bulk density compared to mash diets, thus increasing storage and transportation capacities. Pelleting is also a simple way to create better handling characteristics by improving flowability without altering nutritional properties or adding high costs. At the feed mill, good flow is important when moving ingredients from bulk load-out bins into trucks in order to keep loading times to a minimum. Proper flow out of the bulk feed truck keeps unloading times as short as possible and can also decrease clean-up times as less material will bridge in low-flow areas. Flowability is especially important in automated feed lines where bridging can cause damage to equipment and may leave feeders unfilled. In order for pelleted feeds to reach maximum potential in improving handling characteristics, pellet quality must be considered.

Though improved material handling and feed efficiency will often offset the additional expense of pelleting, costs are always an important consideration to the feed producer. Costs associated with pelleting include the production of steam for conditioning and electrical energy to operate the pellet mill, feeders and conditioner, and pellet cooling system. There are also maintenance and overhead costs such as pellet die and roll assembly reconditioning and replacement. Of these costs, electrical energy is typically considered the most important to observe, as steam production and overhead costs, while high (up to 72% of the energy required to pellet may be used for steam conditioning according to Skoch et al. (1983)), are relatively fixed considering the tons of feed produced, assuming that proper preventative maintenance procedures are followed. The energy costs associated with operating the feeders and conditioners is largely ignored, as the cost to operate them is typically independent of the diet and because the motors used are small compared to the motor driving the pellet mill.

Energy usage at the pellet mill is generally reported as kilowatt-hours per ton (Kwh/ton), with lower values corresponding to less energy usage. Kwh/ton is minimized by operating at the maximum possible production rate based on diet characteristics, die volume, or, most typically, motor load. When production rate is based on maximum motor load, less mechanical energy required at the die will lead to higher production rates. Factors within the diet may affect electrical energy usage based on mechanical energy requirements by affecting friction within the die or because of compaction characteristics of the mash.

The addition of fat to the diet can increase mill efficiency, as found by Stark (1994), likely by acting as a lubricating agent in the pellet die. However, the addition of fat or oils will not always affect pellet mill efficiency (Briggs et al. 1999), possibly because of interactions with other ingredients or specific pelleting conditions. Lubrication of the die is also associated with moisture addition. While this may occasionally be done at the mixer by adding water, moisture is typically added through steam conditioning prior to pelleting. A major variable in steam conditioning is residence time within the conditioner, as greater residence time allows for greater moisture absorption by the mash. Briggs et al. (1999) found that changing the pitch of the conditioner paddles, and thus increasing residence time, increased pellet mill efficiency ($p<0.05$).

Pellet die L:D ratio can also have an effect on pelleting efficiency. Traylor (1997) reported that as pellet size increases both production rate and efficiency increase. Pellet die hole sizes of 2, 4, 8, and 12 mm were used, and while die thickness is not mentioned, knowledge of the pellet die inventory at Kansas State leads to the assumption that as pellet diameter increased, die L:D ratio decreased. This leads to a conclusion that lower L:D ratios lead to increased production rates and improved pellet mill efficiency.

Work done by Stevens (1987) examined the effects of particle size of ground corn and die speed on pelleting. While no effect ($p>0.05$) of particle size on production rate was found, coarse ground corn did reduce pellet mill efficiency ($p<0.05$) in comparison with a medium ground corn. It is theorized that this is because of the extra energy required to force the coarse particles into the die holes. As for the effect of die speed, low correlations were found between die speed and production rate and efficiency.

Pellet quality is important from a processing standpoint because of the effects of pellets on material handling as discussed above. Both ingredient and processing variables may affect pellet quality, and are important considerations when formulating a diet or preparing a pelleting profile (conditioning temperature, die L:D ratio, production rate). From an ingredient standpoint, research has shown that the most important factors on pellet quality are protein and fat levels in the diet. Increased protein level increases pellet durability, while increased fat or oil content decreases pellet durability (Stark, 1994 and Briggs et al. 1999). Specifically in regards to fat in the diet, research by Stark (1994) showed an addition of 1.5% and 3% fat decreased pellet quality by 2% and 5% respectively.

Pellet die L:D ratio is very influential on pellet quality. Increased L:D ratio typically leads to an increase in pellet quality because of an increase in friction and pressure inside the die, leading to greater pellet compaction. Data from Traylor (1997) shows a substantial decrease in pellet quality as L:D ratio decreases (again assuming that as pellet diameter increased, L:D ratio decreased, as mentioned above), ranging from 90.3 to 70.5% in nursery diets and 93.4 to 81.9% in finishing diets.

Both fat and L:D ratio provide an inverse relationship between pellet quality and pellet mill efficiency. This is because increased friction and pressure, while creating higher quality pellets, hampers energy efficiency. However, this is not the case when examining the effect of steam conditioning on pellet quality. Stark (1994) reported that an increase in conditioning temperature improved pellet quality. Similar effects were observed by Briggs et al. (1999) where longer conditioner residence time produced better quality pellets. This shows the importance of steam conditioning, as proper management will lead to better pellet quality and pellet mill efficiency.

Particle size may affect pellet quality, though practical grind sizes based on hammer mill throughput requirements tend to keep particle size in the ranges where no significance on pellet quality is found. Stevens (1987) found no effect of particle size on PDI ($p>0.05$) with corn in the diet ground to 1023, 794, and 551 microns yielding PDI values of 89.9, 88.8, and 90.3% respectively. However, it was noted that pelleting the diet containing the coarse particles resulted in a greater percentage of fines, and it was theorized that the coarse particles created fracture points within the pellet. Stark (1994) found that particle size of the overall diet did significantly affect pellet quality ($p<0.01$), with corn/soy diets with particle sizes of 543 and 233 microns yielding PDI values of 97.3 and 98.5% respectively.

Finally, Stevens (1987) found that there were no practical differences in PDI or fines production across die speeds, and Briggs et al. (1999) noted the correlation between PDI and fines production, showing that low PDI pellets yielded higher fines production. While this is generally true, it may not always be the case as fine particle size ingredients and pellet mill component wear may lead to high fines production even with acceptable PDI values.

## *Nutrition*

Pelleting is an important part of feeding not only from a physical form and material handling standpoint, but is also important to nutrition in the sense of affecting animal growth. Much research has been done regarding the effects of pelleted feeds, mostly focusing on ADG, G/F, and ADFI. And while little work has been done directly regarding the effects of mash versus pelleted diets containing DDGS, pelleting broiler or swine diets with DDGS may lead to improved animal performance based on the information described in this section.

Research concerning the effects of pelleting on the growth and feed performance of swine has been conducted for a long period of time. Focus has been placed on the pelleting process itself, nutrient changes due to pelleting, and pellet quality. Early research by Jensen and Becker (1965) demonstrated that in young pigs, G/F was significantly improved ($p<0.05$) by pelleting corn-soy diets, but ADG was unaffected. A study by Skoch et al. (1983) shows no differences ($p>0.05$) in weanling pig ADG, ADFI, or G/F when using pelleted diets. In the same study a second experiment was conducted with grow-finish pigs, and while there was no improvement in ADFI or ADG, there was a significant improvement ($p<0.05$) in G/F with pelleting, meaning there may be a difference in how weanling pigs and grow-finish pigs respond to pelleted diets.

In some studies, improvements in both G/F and ADG from pelleting have been found in growing and finishing pigs (Hanke et al. 1972, Wondra et al. 1995). Hanke et al. (1972) found that pelleting of corn-soy diets resulted in an increase ($p<0.01$) in ADG and a significant improvement ($p<0.05$) in G/F. Similarly, Wondra et al. (1995) found that pelleting significantly increased ADG ($p<0.01$) and G/F ($p<0.001$) by 5 and 7%, respectively. The study also concluded that apparent digestibility of DM and nitrogen (N) were increased by pelleting ($p<0.001$). Similar results were found by Traylor (1997), with pelleted diets yielding improved digestibilities of DM and N ($p<0.001$), improved G/F ($p<0.04$) of 4% in nursery pigs, and improved ADFI ($p<0.02$) and G/F ($p<0.08$) in finishing pigs.

The effects of pellet quality on growth performance and feed efficiency were examined by Stark (1994). Two nursery experiments were conducted with treatments consisting of mash, pelleted, and pelleted with added fines diets. In the first experiment, no difference in ADG ($p>0.17$) was noted among treatments, though the addition of 25% fines did appear to reduce G/F ($p<0.07$). The second experiment noted no difference in ADG or G/F because of added fines. In both experiments, daily fines accumulation more than doubled when the diets containing fines were fed. In addition, experiment two showed improvements in ADG ($p<0.06$) and G/F ($p<0.01$) of 8 and 15%, respectively, along with greater DM and N digestibility ($p<0.01$) when feeding pellets versus mash diets, which agrees with research presented above. A finishing study was also conducted. There was no effect on animal performance by diet form, and digestibility of DM was improved ($p<0.01$) by pelleting while digestibility of N was not affected by diet form or fines. The presence of fines in the diets did tend to decrease G/F (linear effect, $p<0.09$).

Pelleting of swine diets appears to have beneficial effects on the growth performance of swine. While pelleting seems to improve digestibility, the mechanism for how this occurs is unclear, such as whether the effects on digestion are results of physical form of the diet (i.e. pellet versus mash), changes in nutrient composition or availability, or pellet quality. However, pelleting does appear to increase G/F, likely due to reduced feed wastage, and in many cases improves ADG as well. High percentages of fines decrease feed efficiency, with younger pigs appearing to be more affected than finishing pigs. From a qualitative standpoint, pelleting also reduces segregation and prevents the pig from sorting out palatable ingredients, thus improving the chance of feeding a uniform and balanced diet.

Pelleting and pellet quality have also been the object of research in the feeding of broilers. And though definitive reasons are still being studied, research generally shows that pelleted feed yields positive effects on growth and efficiency (Kilburn and Edwards, 2001, Greenwood et al. 2004, McKinney and Teeter, 2004). Almost all broiler feeds, in integrated operations and produced at commercial feed mills, are pelleted. However, pellet quality is typically poor, with concerns being greater for throughput and energy efficiency rather than for producing high quality pellets. This fact has led researchers to question if there is an effect of pellet quality on animal performance, and whether making efforts to produce higher quality pellets would be justified.

Greenwood et al. (2004) conducted an experiment to examine the effect of feed fines level on the growth of broilers. Both body weight gain (BWG) and average feed intake (AFI) decreased ($p<0.001$) as the level of fines increased from 20 to 60%. No significant effect was observed on feed efficiency. McKinney and Teeter (2004) conducted a study that observed the effects of pellet versus mash feeding as well as the effect of pellet quality on bird performance.

In the experiment birds were fed diets with 100, 80, 60, 40, and 20% pellets with the remainder of the rations being fines. A mash treatment was also fed to act as a negative control. Neither pelleting nor pellet quality had a significant effect on feed intake ($p=0.5$), though birds did selectively consume pellets over fines, with selectivity decreasing as the level of fines in the diet increased. Both pelleting and level of fines had a significant effect on BWG ($p<0.01$ and $p<0.001$, respectively) with pelleting improving BWG by 6% over mash. Improved feed efficiency was also observed as fines decreased ($p<0.01$), and pelleted diets yielded a 5% improvement in efficiency over the mash treatment. Data from this study also suggests that 40% pellet quality is the minimum necessary pellet quality to observe positive nutritional effects from pelleting, and that birds eat less frequently and rest more frequently as the proportion of pellets in the diet increases.

Pelleting broiler diets improves growth and feed efficiency over mash diets, and the reduction of fines in pelleted diets will lead to better overall performance. Research suggests that this is because of reduced energy requirements during feed consumption as well decreased segregation and sorting by the bird. Pairing this with the knowledge that increased pellet quality will lead to better flow through feed systems and increased storage capacity, it seems that being concerned about producing good quality pellets is an important and necessary step in feed production.

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# CHAPTER 1 - The Effect of Substituting DDGS for Corn on Pellet Quality and Pellet Mill Efficiency

## Introduction

Research using pelleted diets has provided an unclear picture of how the inclusion of DDGS affects pellet characteristics, such as pellet quality and bulk density. Industry belief is that increased use of DDGS leads to a decrease in pellet quality, and research published to date has generally supported this idea. Studies have found that, with increasing DDGS in the diet, visual pellet quality decreases and there are increased levels of fines in the finished feed (Wang et al. 2007a, Min et al. 2008). Though few in number, some studies have objectively measured pellet quality using standardized procedures, and conflicting results have been reported. Pellet durability has been shown to both decrease (Stender et al. 2008) and increase (Feoli, 2008) with increasing DDGS in the diet.

Concerning bulk density, data has shown a decrease in bulk density as the percentage of DDGS in the diet increases (Wang et al. 2007b), which is expected considering the physical properties of DDGS and the ingredients being replaced in the diet (generally ground corn and soybean meal). Little or no consideration has been given to the effects, if any, that the incorporation of DDGS in corn-soy diets may have on production rate and energy consumption at the pellet mill. However, these two factors may be the most important to commercial feed processing from an economic standpoint.

# Materials and Methods

## *General*

Two experiments were conducted to determine the effect of DDGS inclusion level in a corn-soy diet on pellet quality and pellet mill efficiency. Corn-based DDGS were obtained from a new generation ethanol plant, and corn and soybean meal were obtained from a local elevator. All production runs were completed at the Feed Processing Research Center in the Department of Grain Science at Kansas State University (KSU) using a 30 HP California Pellet Mill (Crawfordsville, IN) 1000 series "Master HD" model pellet mill equipped with a 3.97 mm (5/32") x 31.75 mm (1 ¼") (hole diameter vs. effective die thickness) pellet die. Feed was steam conditioned prior to pelleting using a Bliss Industries (Ponca City, OK) 30.5 cm (12") by 121.9 cm (48") steam conditioner. All treatments for both experiments were conditioned with the same retention time, which was set using a variable frequency drive (VFD) and to the same temperature of 85°C (185°F). The mash feeder screw, which feeds the steam conditioner, was also set to a constant RPM for all treatments using a variable frequency drive (VFD).

In the initial experiment, only the major ingredient, corn, was varied as DDGS were added at levels of 0, 10, 20, 30, and 40% (Table 1-1). This single variation was done in an attempt to negate any effects that changes in other ingredients, such as soybean meal and minerals, might have on pellet quality. No attention was given to the overall nutritional balance of the diet in this experiment. In the second experiment diets were formulated to maintain minimum NRC (1998) requirements for protein, calcium, phosphorus, and amino acids in growing swine (Table 1-2), and all ingredients were allowed to vary to maintain these minimum levels. This was done to provide an ingredient platform more representative of a typical commercially produced swine diet. However, diets were not kept isocaloric, as doing so would have required the addition of varying levels of liquid fat, and the addition of fat could have affected pellet quality and pellet mill efficiency (Stark, 1994). In the interest of pellet quality, fat could be post-coated onto the pellets at the feed mill to meet energy requirements.

## ***Data Collection***

Pellet quality was measured using the tumbling box procedure ASAE S269.4 (ASAE, 1991) and results are reported as the pellet durability index (PDI). Pellets were collected directly from the pellet mill and cooled with forced air in trays using a locally constructed batch cooler. Two standard and two modified (inclusion of five 12.7 mm (½”) hex nuts) PDI tests were conducted for each production run, and an average value for each was determined. Feed production rate was measured directly at the pellet mill by collecting pellets from the discharge of the pellet mill for 15 seconds and calculating production in kilograms per hour. This was done three times throughout each production run at equal intervals and an average value was determined and used as the production rate for the run. Electrical energy data was collected using an Amprobe (Miami, FL) DMII (Pro) Data Logger Recorder and was used to calculate energy consumption in kilowatt-hours per ton (Kwh/ton) for each production run. Bulk density of pellets and of mash prior to pelleting was determined using a Seedburo (Chicago, IL) Model 8860 High Capacity Grain/Test Weight Scale. Three bulk density samples were taken for each feed form during each production run, and the values were averaged. For experiment 1, the bulk density of pellets was determined using pellets taken from the batch cooler, while in experiment 2, pellets from the batch cooler and from the sack-off bin were used to determine how sampling location impacts PDI.

### *Statistical Analysis*

Both experiment 1 and 2 were run as randomized complete block designs (RCBD) with the treatments of 0, 10, 20, 30, and 40% added DDGS being randomized within a block. Treatments within a block were run in random order at similar times on the same day in order to suppress any environmental sources of variation. Three replications of each treatment were conducted, with each replication being a single production run. Data was analyzed using the general linear model (GLM) of SAS (v. 9.1). Analyses were completed for standard PDI, modified PDI, production rate, energy usage, mash bulk density, and pellet bulk density. Treatments were compared using Tukey's studentized range test to analyze all pair-wise comparisons. Pair-wise comparisons were used because, while level of DDGS may have a significant overall effect, there may be no significant difference between specific levels of DDGS. Direct comparison of two treatments is valuable in the case of wanting to determine if changing the current use level by 10% will have a significant effect.

## Results

### *Experiment 1*

Results of experiment 1 are presented in Table 1-3. The level of DDGS inclusion had no effect on either standard PDI ($p>0.24$) or modified PDI ($p>0.34$) values, and overall feed appearance was acceptable at the pellet mill and at the sack-off bin across all treatments. Increasing DDGS inclusion had a significant ($p<0.0001$) effect on production rate, with 40% DDGS yielding a 10% lower production rate than the corn-soy control. There was no significant difference between the corn-soy control and 10% DDGS. There was a statistically significant effect ($p<0.04$) on energy consumption, though pair-wise analysis shows that only the control diet and the diet containing 20% DDGS were significantly different. Increasing levels of DDGS led to significantly lower mash bulk density ($p<0.005$), with 30 and 40% DDGS differing from the control, and pellet bulk density ($p<0.0001$), with all levels differing from the control.

### *Experiment 2*

Results of experiment 2 are presented in Table 1-4. Pellet quality decreased significantly as DDGS inclusion increased according to both standard and modified PDI values (both $p<0.005$). However, 10% added DDGS did not differ from the control in either case and, as in experiment 1, PDI values were well above 80%, which would be within the generally accepted range for swine and poultry feed producers. Increasing DDGS negatively affected production rate ($p<0.0004$); incorporating 40% DDGS decreased production rate by 13% over the corn-soy control. Again, there was no significant difference between the corn-soy control and 10% DDGS. There was no significant effect on energy consumption ($p>0.12$). DDGS level significantly affected both mash and pellet bulk density (both $p<0.0001$), as an increase in DDGS led to a decrease in bulk density; all levels varied from the control as mash, and only 10% DDGS was similar to the control in pellets.

## Discussion

Pellet quality, while statistically significant in experiment 2, was not dramatically affected from a practical standpoint by the inclusion of DDGS. Overall PDI values were adequately high in both experiments, and the general visual quality of the feed did not appear to suffer with the addition of DDGS. Similarly, energy consumption was not generally affected, meaning there is no increased electrical cost associated with the pelleting of diets containing DDGS.

The inclusion of DDGS had the greatest effect on production rate and bulk density of both the mash and finished pellets. Because of the processing parameters set forward previously, it can be explained that the decrease in production rate is tied to the decrease in bulk density. The mash feeder screw was set to a constant RPM using a VFD in order to remove human error that would be inherent in attempting to set production rate or energy consumption. A screw feeder is a volumetric metering device and mass discharge rate is therefore dependent on the bulk density of the material being moved. Because the bulk density of the mash decreases, and because the feeder screw speed is fixed, it follows that production rate would decrease as well. This is an important issue because, in automated feed manufacturing systems, pellet mill production rate is set by the feeder screw VFD, which is controlled by the system. If the system is programmed to operate by maintaining a constant production rate (versus motor load or Kwh/ton), the system will set the VFD to run the feeder screw at the same RPM for a given production rate independent of the mash. Thus, updating the bulk density value within the system can be very important to maintaining desired production. It should be noted that this same logic applies to any feeder systems that are not weight-controlled, whether part of an automated system or a stand-alone device.

A secondary issue concerning experiments 1 and 2 is the correlation between mash bulk density and pellet bulk density. As seen in Table 1-3, pellet bulk density is less than the mash bulk density for each treatment from experiment 1. As mentioned previously, pellet samples for experiment 1 were taken from the PDI batch cooler, while samples for experiment 2 were taken from the both the sack-off bin and the batch cooler (Table 1-4), in order to examine the effect of sampling location on bulk density. It is clear that pellets taken from the sack-off bin have higher bulk densities than pellets from the batch cooler. This is because pellets in the sack-off bin have an increased level of fines, generated as the pellets move through the processing system, while the samples from the batch cooler have virtually no fines. This agrees with data shown by Wilson and McKinney (2008) that bulk density is highest with a moderate level of fines mixed with the pellets. Pellets mixed with fines may have greater bulk densities than sifted pellets because the fines act to fill interstitial spaces left between the regularly shaped pellets. This data demonstrates the importance of taking bulk density samples from a finished product location rather than directly at the pellet mill in order to obtain commercially representative values.

## Implications

Pelleting was shown to be unaffected by the inclusion of 10% DDGS, and feasible for diets containing up to 40% DDGS. Pellet quality is adequate, and there are no extra associated electrical costs at the pellet mill. Maintaining accurate and updated bulk density values within an automated control system, or adjusting manually operated mash feeding equipment, is important when using DDGS because of the changes in bulk density as inclusion rates vary.

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**Table 1-1: Composition of experimental diets (Exp.1)**

| | | DDGS Level | | | |
|---|---|---|---|---|---|
| Ingredient | Control | 10% | 20% | 30% | 40% |
| Corn | 75.00 | 65.00 | 55.00 | 45.00 | 35.00 |
| DDGS | - | 10.00 | 20.00 | 30.00 | 40.00 |
| Soybean Meal | 20.00 | 20.00 | 20.00 | 20.00 | 20.00 |
| | | | | | |
| Monocalcium phosphate | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 |
| Limestone | 1.25 | 1.25 | 1.25 | 1.25 | 1.25 |
| Salt | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| | | | | | |
| Soybean Oil | 2.00 | 2.00 | 2.00 | 2.00 | 2.00 |

**Table 1-2: Composition of experimental diets (Exp. 2)**

| | | DDGS Level | | | |
|---|---|---|---|---|---|
| Ingredient | Control | 10% | 20% | 30% | 40% |
| Corn | 79.64 | 72.77 | 66.17 | 59.67 | 52.91 |
| Soybean Meal | 17.80 | 14.80 | 11.50 | 8.10 | 4.95 |
| DDGS | - | 10.00 | 20.00 | 30.00 | 40.00 |
| | | | | | |
| Monocalcium phosphate | 0.74 | 0.56 | 0.40 | 0.22 | 0.05 |
| Limestone | 1.09 | 1.15 | 1.21 | 1.28 | 1.34 |
| L-lysine HCl | 0.20 | 0.26 | 0.33 | 0.40 | 0.47 |
| L-threonine | 0.03 | 0.01 | | | |
| Salt | 0.43 | 0.37 | 0.31 | 0.26 | 0.20 |
| Vitamin premix | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Trace mineral premix | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 |

**Table 1-3: Effects of DDGS level on processing and pellet quality (Exp. 1)**

| | | DDGS Level | | | |
|---|---|---|---|---|---|
| | Control | 10% | 20% | 30% | 40% |
| Std. PDI (%) | 85.17 | 84.86 | 85.94 | 85.40 | 83.21 |
| Mod. PDI (%) | 80.77 | 81.36 | 82.39 | 81.77 | 79.39 |
| Production rate (kg/hr) | $965^{a}$ | $941^{a,b}$ | 930 b | $898^{c}$ | $870^{c}$ |
| Kwh/ton | $11.30^{a}$ | $10.83^{a,b}$ | $10.81^{b}$ | $10.87^{a,b}$ | $11.08^{a,b}$ |
| Mash bulk density (Kg/hL) | $60.06^{a}$ | $58.78^{a,b}$ | $57.98^{a,b,c}$ | $57.19^{b,c}$ | $55.70^{c}$ |
| Pellet bulk density (Kg/hL) | $56.61^{a}$ | $54.47^{b}$ | $53.92^{b}$ | $52.62^{b}$ | $50.19^{c}$ |

$^{a,b,c}$ Means within a row with differing superscripts differ ($p<0.05$)

**Table 1-4: Effects of DDGS level on processing and pellet quality (Exp. 2)**

| | | DDGS Level | | | |
|---|---|---|---|---|---|
| | Control | 10% | 20% | 30% | 40% |
| Std. PDI (%) | 90.32 $^{a}$ | 88.28 $^{a,b}$ | 86.83 $^{b}$ | 85.43 $^{b}$ | 86.65 $^{b}$ |
| Mod. PDI (%) | 88.58 $^{a}$ | 87.15 $^{a,b}$ | 84.57 $^{b,c}$ | 83.04 $^{c}$ | 84.26 $^{b,c}$ |
| Production rate (kg/hr) | 1009 $^{a}$ | 977 $^{a}$ | 912 $^{b}$ | 891 $^{b}$ | 890 $^{b}$ |
| Kwh/ton | 11.39 | 11.36 | 11.69 | 11.72 | 11.73 |
| Mash bulk density (Kg/hL) | 58.69 $^{a}$ | 56.94 $^{b}$ | 55.30 $^{c}$ | 53.22 $^{d}$ | 52.81 $^{d}$ |
| Pellet bulk density (Kg/hL) (from sack-off) | 63.21 $^{a}$ | 61.97 $^{a}$ | 59.40 $^{b}$ | 57.94 $^{b,c}$ | 56.93 $^{c}$ |
| Pellet bulk density (Kg/hL) (from batch cooler) | 57.88 $^{a}$ | 56.27 $^{b}$ | 54.08 $^{c}$ | 51.80 $^{d}$ | 51.17 $^{d}$ |

$^{a,b,c,d}$ Means within a row with differing superscripts differ ($p<0.05$)

# CHAPTER 2 - Effects of Using Increasing Inclusion Rates of Pelleted and Reground DDGS in Corn-Soy Diets on Pellet Quality and Pelleting Efficiency

## Introduction

DDGS are known for poor flow characteristics and low bulk density (48-56 Kg/hL or 30-35 lbs/ft$^3$), both issues which contribute to problems in material handling. DDGS tend to hang up in spouting, and often bridge up in storage bins as well as in transportation vessels such as trucks or rail cars. This bridging results in increased unloading times, and increased labor costs, along with damage to trucks and railcars as force must often be used to remove the DDGS during unloading. In addition, poor bulk density means that less DDGS can be stored in existing bin space and also leads to increases in transportation costs as trucks and rail cars may be filled before reaching maximum weight allowance.

Pelleting may be one possible way to solve some of the material handling issues inherent to DDGS. Pelleting 100% DDGS has been shown to be possible (AURI, 2005, Wilson and McKinney, 2008), and could be done directly at the ethanol plant prior to shipping. Improvements in bulk density have been noted, along with an increased pellet durability as the ratio of pellet die width to pellet diameter, commonly known as the L:D ratio, is increased (AURI, 2005, Wilson and McKinney, 2008). Increased bulk density would improve cost of shipping as vessels could be loaded closer to maximum weight capacity. Pelleting may also enhance flowability by creating a more uniform product and by reducing surface area, which would limit friction and cohesion.

Pelleted DDGS would have to be reground before being included as an ingredient in a pelleted feed. The use of pelleted and reground DDGS has not been thoroughly studied; however, the use of a pelleted and reground wheat middlings (midds) has met with success (Fahrenholz, 1989). Pelleted and reground midds were shown to have higher bulk densities than unprocessed midds, which means an increase in storage and transportation capacity. Also, pelleted diets containing pelleted and reground midds yielded higher production rates, lower energy, and roughly similar pellet quality when compared to pelleted diets containing unprocessed midds. If pelleted and reground DDGS can be used in pelleted diets with similar results, then this would be even more reason to pursue the pelleting of DDGS at the ethanol plant.

## Materials and Methods

### *General*

An experiment was conducted to determine the effect of using pelleted and reground (PRG) DDGS compared to unprocessed (UNP) DDGS at increasing inclusion levels in a corn-soy diet on pellet quality and pellet mill efficiency. Corn-based DDGS were obtained from a new generation ethanol plant, and corn and soybean meal were obtained from a local elevator. Pelleted DDGS were produced using a 30 HP California Pellet Mill (Crawfordsville, IN) 1000 series “Master HD” model pellet mill equipped with a 3.97 mm (5/32”) x 31.75 mm (1 ¼”) (hole diameter vs. effective die thickness) pellet die. The DDGS were steam conditioned prior to pelleting using a Bliss Industries (Ponca City, OK) 30.5 cm (12”) by 121.9 cm (48”) steam conditioner. The DDGS pellets were then allowed to equilibrate for 3 weeks prior to grinding in order to represent time of transportation and storage between processing at the ethanol plant and feed mill use. The pelleted DDGS were ground using a 30 HP Jacobsen Machine Works Model P-240 full circle hammermill (Minneapolis, MN) equipped with a 3.18mm (1/8”) screen.

PRG and UNP DDGS were incorporated into corn-soy diets at levels of 0, 10, 20, and 30%. Diets were pelleted using the same equipment listed for the processing of the DDGS pellets. All treatments were conditioned with the same retention time, which was set using a variable frequency drive (VFD) and to the same temperature of 85°C (185°F). The mash feeder screw, which feeds the steam conditioner, was also set to a constant RPM for all treatments using VFD control.

Diets were formulated to maintain minimum NRC (1998) requirements for protein, calcium, phosphorus, and amino acids in growing swine (Table 2-1), and all ingredients were allowed to vary to maintain these minimum levels. Diets were not kept isocaloric, as doing so would have required the addition of varying levels of liquid fat, and the addition of fat could have affected pellet quality and pellet mill efficiency (Stark, 1994). Supplemental fat could be post-coated onto the pellets at the feed mill to meet energy requirements.

### *Data Collection*

Pellet quality was measured using the tumbling box procedure, ASAE S269.4 (ASAE, 1991), and results are reported as the pellet durability index (PDI). Pellets were collected directly from the pellet mill and cooled with forced air in trays using a locally constructed batch cooler. Two standard and two modified (inclusion of five 12.7 mm (½”) hex nuts) PDI tests were conducted for each production run, and an average value for each was determined. Feed production rate was measured directly at the pellet mill by collecting pellets from the discharge of the pellet mill for 15 seconds and calculating production in kilograms per hour. This was done three times throughout each production run at equal intervals and an average value was determined and used as the production rate for the run. Electrical energy data was collected using an Amprobe (Miami, FL) DMII (Pro) Data Logger Recorder and was used to calculate energy consumption in kilowatt-hours per ton (Kwh/ton) for each production run. Bulk density of pellets and of mash prior to pelleting was determined using a Seedburo (Chicago, IL) Model 8860 High Capacity Grain/Test Weight Scale. Three bulk density samples were taken for each feed form during each production run, and the values were averaged. Particle size of corn, UNP DDGS, and PRG DDGS was measured using a W.S. Tyler Inc. (Mentor, OH) Ro-Tap Testing Sieve Shaker, Model B, and according to methods described in ASAE S319.3 (ASAE, 2003).

### ***Statistical Analysis***

The experiment was run as a randomized complete block design (RCBD) with the control (0% DDGS) and treatments of 10, 20, and 30% added PRG and UNP DDGS being randomized within a block. Treatments within a block were run in random order on the same day in order to suppress any environmental sources of variation. Three replications of each treatment were conducted, with each replication being a single production run. Data was analyzed using the general linear model (GLM) of SAS (v. 9.1). Analyses were completed for standard PDI, modified PDI, production rate, energy usage, mash bulk density, and pellet bulk density.

The data was then analyzed in two ways. The seven treatments (one control, three levels of UNP DDGS, three levels of PRG DDGS) were compared using Tukey's studentized range test to analyze all pair-wise comparisons. Pair-wise comparisons were used to make comparisons between the treatments and the control and between treatments themselves. A factorial design model was also used to analyze the data. In this case both DDGS type and level were analyzed in a blocked 2 x 3 factorial design. The control was omitted from this analysis in order to avoid an unbalanced design. This method is used to make inferences on the effects of both DDGS type and inclusion level, along with any apparent interactions. .

## Results

Table 2-2 illustrates the effect of pelleting and regrinding DDGS. Average particle size was smaller for the PRG DDGS compared to UNP DDGS, and was also smaller than the ground corn used in the diets. PRG DDGS had higher apparent bulk density than UNP DDGS.

Results of the pelleting experiment are presented in Table 2-3. Standard PDI values were increased by using PRG DDGS ($p<0.0001$), while level had no significant effect ($p>0.45$) among the DDGS treatments. There was no significant interaction. Pair-wise analysis shows that all PRG DDGS levels had PDI values similar to the control, while only the 10% level of UNP DDGS was similar. Modified PDI values show a similar trend, with PRG DDGS yielding higher pellet quality ($p<0.0001$) and level having no effect on PDI ($p>0.10$) among the DDGS treatments. However, there was significant interaction ($p<0.02$), and this is supported by the pair-wise analysis. It appears that while pellet quality tends to decrease as the level of UNP DDGS is increased, there is no change in pellet quality among the PRG DDGS treatments. Again, only the 10% UNP DDGS treatment is similar to the control, while all PRG DDGS treatments are similar.

Production rate was significantly affected by both level ($p<0.0001$) and type ($p<0.02$) among the DDGS treatments, with increasing levels of DDGS leading to decreased production rate, and diets containing PRG DDGS having higher production rates than diets containing UNP DDGS. There was no interaction. Pair-wise analysis does not appear to support the significance of DDGS type, and this is because of the inclusion of the control in the analysis. However, in direct comparison there does appear to be a difference between the UNP and PRG treatments, notably at the levels of 20% (929 and 958 kilograms per hour respectively) and 30% (911 and 933 kilograms per hour respectively). All DDGS treatments differed from the control.

Diets containing PRG DDGS required less energy to pellet ($p<0.01$) than diets containing UNP DDGS, while DDGS level had no effect ($p>0.40$) and there was no interaction. Pair-wise analysis supports this data, though no treatment appears to differ significantly from the control. Both mash and pellet density were affected by DDGS type ($p<0.001$ for both) and level ($p<0.0001$ for both). In both cases, diets with PRG DDGS had higher bulk density values, and increasing levels of DDGS led to lower bulk density for both DDGS types. A small interaction ($p=0.0447$) was observed for mash density, and pair-wise analysis shows that there was somewhat less variation in mash density between the levels of 20 and 30% when using PRG DDGS compared to UNP DDGS. All DDGS treatments differed significantly from the control.

## Discussion

The use of PRG over UNP DDGS would likely be preferred by most feed mills given the option simply because of the reduction in labor, increased storage capacity, and generally lower complications of use. The data from this experiment shows there are also benefits to using PRG DDGS from a processing standpoint. Using PRG DDGS increases pellet quality, improves production rate, reduces pellet mill energy consumption, and increases pellet and mash bulk density in comparison to using UNP DDGS.

The reasons for improved pellet quality and pelleting efficiency when using PRG DDGS are unknown. PRG DDGS had a lower particle size in comparison to UNP DDGS, and smaller particle size has been shown to improve pellet quality (Stark, 1994). The increased bulk density of the PRG DDGS over UNP DDGS suggests that the compression of particles that is a result of pelleting is at least partially retained after grinding. This may mean that less energy is required to compress the PRG DDGS during pelleting of the final diets, and that there is less potential for the DDGS to cause separation of ingredients within the pellets by decompression after pelleting. Though not objectively determined, there appeared to be improved flow properties when using PRG DDGS, and this, along with a slightly lower geometric standard deviation ($S_{gw}$) value, may suggest that the shape of the PRG DDGS is more uniform and compact, having less surface area than the equivalent weight of the generally flat UNP DDGS. This would yield more surface area within the pellet for the bonding of other, generally considered more pellet friendly ingredients, such as corn and soybean meal. Finally, some of the properties of DDGS that inhibit material handling, such as solubles level, moisture content, and physical and chemical properties on the surface of the product, may also negatively affect pelleting. By pelleting and regrinding the DDGS prior to use in final pelleted feeds some of these variables may be partially negated.

## Implications

There is evidence to suggest that the use of PRG DDGS can improve production of pelleted diets containing DDGS. And because pelleted DDGS could provide improved handling and lower shipping costs, the use of PRG DDGS may be a solution to a number of the problems associated with the use of DDGS. However, more research in a number of areas needs to be conducted concerning this process. Pelleting DDGS at the ethanol plant would add cost, and an in depth analysis is needed to determine if this cost might be absorbed by savings in transportation, labor, reductions in equipment damage, and increased customer demand. Furthermore, with modifications to the DDGS drying process, it may be possible to reduce the cost of producing pelleted DDGS to equal or even improve upon the cost of producing UNP DDGS by reducing the amount of energy required for drying and steam generation (Appendix A). The two main detriments to using pelleted DDGS are that regrinding would necessitate extra bin space at the feed mill and would add energy cost at the hammer mill, and these two factors need to be examined and taken into account.

In processing, further research needs to be conducted to determine the response of PRG DDGS in pelleted diets when production rate or motor load is held constant, as would be typical in a commercial feed mill. Research should be conducted to determine if there are any notable effects of using PRG DDGS in the feeding of animals, most importantly swine and poultry. And the physical and/or chemical properties that create improved material handling and pelleting characteristics when using PRG DDGS also need to be investigated and addressed.

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**Table 2-1: Composition of experimental diets**

| Ingredient | Control | DDGS Level<br>10% | 20% | 30% | 40% |
|---|---|---|---|---|---|
| Corn | 79.64 | 72.77 | 66.17 | 59.67 | 52.91 |
| Soybean Meal | 17.80 | 14.80 | 11.50 | 8.10 | 4.95 |
| DDGS | - | 10.00 | 20.00 | 30.00 | 40.00 |
| | | | | | |
| Monocalcium phosphate | 0.74 | 0.56 | 0.40 | 0.22 | 0.05 |
| Limestone | 1.09 | 1.15 | 1.21 | 1.28 | 1.34 |
| L-lysine HCl | 0.20 | 0.26 | 0.33 | 0.40 | 0.47 |
| L-threonine | 0.03 | 0.01 | | | |
| Salt | 0.43 | 0.37 | 0.31 | 0.26 | 0.20 |
| Vitamin premix | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 |
| Trace mineral premix | 0.03 | 0.04 | 0.04 | 0.04 | 0.05 |

**Table 2-2: Physical Properties of corn, UNP DDGS, PRG DDGS**

| | $D_{gw}$ (μ) | $S_{gw}$ (μ) | Bulk Density (Kg/hL) |
|---|---|---|---|
| Corn | 646 | 1.96 | 56.12 |
| Unprocessed DDGS | 692 | 2.07 | 45.56 |
| Pelleted-Reground DDGS | 508 | 1.93 | 48.20 |

**Table 2-3: PRG DDGS inclusion vs. UNP DDGS inclusion**

| | | UNP DDGS | | | PRG DDGS | | |
|---|---|---|---|---|---|---|---|
| | Control | 10% | 20% | 30% | 10% | 20% | 30% |
| Std. PDI (%) | $91.84^{a,b}$ | $90.43^{b,c}$ | $89.89^{c}$ | $89.10^{c}$ | $91.55^{a,b}$ | $91.87^{a,b}$ | $91.95^{a}$ |
| Mod. PDI (%) | $90.48^{a}$ | $89.41^{a,b}$ | $88.19^{b,c}$ | $87.31^{c}$ | $90.24^{a}$ | $90.52^{a}$ | $90.69^{a}$ |
| Production rate (kg/hr) | $1007^{a}$ | $974^{b}$ | $929^{c,d}$ | $911^{d}$ | $975^{b}$ | $958^{b,c}$ | $933^{c,d}$ |
| Kwh/ton | $10.72^{a,b,c}$ | $10.73^{a,b,c}$ | $10.84^{a,b}$ | $11.00^{a}$ | $10.54^{a,b,c}$ | $10.31^{c}$ | $10.47^{b,c}$ |
| Mash bulk density (Kg/hL) | $57.99^{a}$ | $56.60^{b,c}$ | $54.73^{d}$ | $53.22^{e}$ | $57.14^{a,b}$ | $55.56^{c,d}$ | $54.98^{d}$ |
| Pellet bulk density (Kg/hL) | $62.43^{a}$ | $60.71^{b,c}$ | $58.66^{d,e}$ | $57.87^{e}$ | $61.77^{a,b}$ | $60.15^{b,c,d}$ | $59.84^{c,d}$ |

$^{a,b,c,d,e}$Means within a row with differing superscripts differ ($p<0.05$)

# Appendix A - Theoretical DDGS Drying and Pelleting Calculations

## DDGS Drying

Assume that a bushel of corn produces 2.7 gallons of ethanol, 18 pounds of carbon dioxide, and 18 pounds of DDGS (Feed International). A 100 million gallon per year ethanol plant would then produce the following amount of DDGS per year:

$$\frac{10^8\ gallons\ ethanol}{year}\left(\frac{18\ lbs\ DDGS}{2.7\ gallons\ ethanol}\right)$$

$$=\frac{6.7x10^8\ lbs\ DDGS}{year}\ or\ \frac{3.3x10^5\ tons\ DDGS\ (G)}{year}$$

Models constructed to predict ethanol production and operation costs have used a production basis of 24 hours per day operation, 330 days per year, with the remaining 35 days being set aside for maintenance and repairs (Kwiatkowski et al. 2006). Using these parameters, the following is the amount of DDGS produced per day and per hour:

$$\frac{6.7x10^8\ lbs\ DDGS}{year}\left(\frac{1\ year}{330\ days}\right)=\frac{2.0x10^6 lbs\ DDGS}{day}\ or\ \frac{1010\ tons\ DDGS}{day}$$

$$\frac{2.0x10^6 lbs\ DDGS}{day}\left(\frac{1\ day}{24\ hours}\right)=\frac{8.4x10^4\ lbs\ DDGS\ (A)}{hour}\ or\ \frac{42\ tons\ DDGS}{hour}$$

Drying of wet distillers grains with solubles (WDGS) to obtain DDGS typically means drying from 65% moisture (35% DM) to 10% moisture (90% DM). To determine the amount of WDGS entering the drum dryer we use the following equation:

$$\frac{8.4x10^4\ lbs\ DDGS}{hour}(90\%\ DM) = \frac{x\ lbs\ WDGS}{hour}(35\%\ DM), x = \frac{2.2x10^5\ lbs\ WDGS}{hour}$$

To dry from 65% moisture to 10% moisture the dryer must remove 1.32x10$^5$ pounds of water per hour (2.2x10$^5$ – 8.4x10$^4$). The model by Kwiatkowski et al. gives a value for the amount of natural gas required to evaporate water on a kilogram per kilogram basis. Knowing this conversion we can determine the amount of natural gas required to remove 1.3x10$^5$ pounds of water per hour:

$$\frac{1.32x10^5 lbs\ water\ (B)}{hour}\left(\frac{1\ kg}{2.20\ lbs}\right)\left(\frac{0.06\ kg\ Natural\ Gas}{1\ kg\ water}\right) = \frac{3.6x10^3 kg\ Natural\ Gas\ (C)}{hour}$$

In July, 2008 the industrial price for natural gas in Kansas was \$10.76/1000ft$^3$ (Energy Information Administration). Because natural gas may include various levels of gases such as methane, propane, and butane, among others, it is difficult to establish a direct energy value. Assuming that the energy content of natural gas is 1000 BTU per cubic foot (1 million BTU per 1000 cubic feet), and that the heating value of propane vapor, 21, 548 BTU/lb, is a good estimator of the energy density of natural gas, the following equation gives the cost per hour of drying:

$$\frac{3.6x10^3 kg\ N.G.}{hour}\left(\frac{2.2\ lbs}{1kg}\right)\left(\frac{21,548\ BTU}{1lb}\right)\left(\frac{1000\ c.f.}{10^6 BTU}\right)\left(\frac{\$10.76}{1000\ c.f.}\right)$$

$$= \frac{\$1840\ (D)}{hour}\ or\ \frac{\$43.72}{ton\ DDGS}$$

## Cost of Pelleting

To conduct pelleting at an ethanol plant, equipment would have to be purchased. Assume that purchasing and installing all of the necessary equipment such as supply bins, pellet mill, steam system, and cooler totaled one million dollars. If the lifespan of the equipment is 25 years, and pelleting occurs at the same rate of DDGS production, the following equation demonstrates the cost per ton associated with equipment costs:

$$\frac{\$10^6\ equipment\ costs}{25\ year\ lifespan}\left(\frac{1\ year}{3.3x10^5\ tons\ DDGS}\right)=\frac{\$0.120}{ton\ DDGS}$$

To pellet DDGS will likely require one employee to monitor the equipment and perform routine maintenance. Assuming a salary of $35,000 per year, the following equation demonstrates the cost per ton associated with labor:

$$\frac{\$35{,}000\ salary}{year}\left(\frac{1\ year}{3.3x10^5\ tons\ DDGS}\right)=\frac{\$0.105}{ton\ DDGS}$$

Die and roll replacement will be the most common maintenance costs for pelleting DDGS. Assuming a new die costs approximately $10,000 and each roll assembly costs $3000 (2 roll assemblies required), and that replacement would be done three times a year, the following equation demonstrates the cost per ton associated with replacement of the die and rolls:

$$\frac{\$16{,}000}{replacement}\left(\frac{3\ replacments}{year}\right)\left(\frac{1\ year}{3.3x10^5\ tons\ DDGS}\right)=\frac{\$0.144}{ton\ DDGS}$$

Electrical costs are a large component of pelleting cost. The factors that account for energy cost are the number of kilowatt hours used, which may be determined by knowing the total connected horsepower and the production rate, which we will assume to be the same as the rate of DDGS produced. Assuming that the pellet mill has a 400 horsepower motor, and that all other motors connected total 100 horsepower collectively, the amount of kilowatt hours per ton can be calculated as below:

$$500\ total\ \ HP\left(\frac{0.7457\ kilowatt\ hour}{1\ horsepower\ hour}\right)\left(\frac{1\ hour}{42\ tons\ DDGS}\right)=\frac{8.86\ kilowatt\ hours\ (kwh)\ (F)}{ton\ DDGS}$$

In June 2008, the industrial price for electricity in Kansas was \$0.063/kwh (Energy Information Administration). The equation below determines the cost per ton for electricity usage:

$$\frac{8.86\ kwh}{ton\ DDGS}\left(\frac{\$0.063}{kwh}\right)=\frac{\$0.558\ (H)}{ton\ DDGS}$$

Electrical motors do not run at 100 percent efficiency, and the energy company charges a penalty fee for this lack of efficiency. Assuming a 90 percent motor efficiency (also known as power factor) the amount of penalty per ton can be calculated as below:

$$\frac{\$0.558}{ton\ DDGS}(10\%\ Penalty)=\frac{\$0.056}{ton\ DDGS}$$

There is also a demand charge based on the maximum usage during a 15 to 30 minute period during the month. Assuming that the equipment runs at a constant 500 HP load, and that the demand charge is approximately \$7.50/kW, the cost per ton of the demand charge can be determined:

$$500\ HP\left(\frac{0.7457\ kilowatt}{1\ HP}\right)\left(\frac{\$7.50}{kilowatt}\right)=\frac{\$2796.375}{month}$$

$$\frac{\$2796.375}{month}\left(\frac{12\ months}{1\ year}\right)\left(\frac{1\ year}{3.3x10^5\ tons\ DDGS}\right)=\frac{\$0.101\ (I)}{ton\ DDGS}$$

The total cost of electricity can then be determined by adding together the usage cost, the power factor penalty, and the demand charge:

| | |
|---|---|
| Usage Cost: | \$0.558/ton DDGS |
| Power Factor Penalty: | \$0.056/ton DDGS |
| Demand Charge: | \$0.101/ton DDGS |
| | \$0.715/ton DDGS |

To successfully pellet DDGS the moisture content of the mash entering the pellet mill should be at or near 16%. This is typically done by adding steam in a conditioner. Steam is generated using a boiler, and this cost will factor into the cost of pelleting. Assuming the pelleting will be done at the rate of DDGS produced, the amount of steam required can be determined as below:

$$\frac{8.4x10^4\ lbs\ DDGS}{hour}(90\%\ DM) = \frac{x\ lbs\ conditioned\ DDGS}{hour}\ (84\%\ DM), x = \frac{9.0x10^4\ lbs}{hour}$$

This is equivalent to $6.0x10^3$ lbs of steam required per hour. Assuming that the steam being used is 30 pounds per square inch, by using steam tables we can determine that there is roughly 1164.3 BTU per pound of steam. We also assume that a steam boiler is not 100% efficient; assuming a 75% efficiency, the following equation calculates the BTU required to generate the required steam:

$$\frac{\frac{6.0x10^3 lbs\ steam}{hour}\left(\frac{1164.3\ BTU}{1\ lb\ steam}\right)}{75\%\ Efficiency} = \frac{9.3x10^6\ BTU}{hour}$$

Knowing the cost of natural gas (used previously) and the production rate, the cost per ton for steam generation can be determined:

$$\frac{9.3x10^6\ BTU}{hour}\left(\frac{1000\ c.f.}{10^6 BTU}\right)\left(\frac{\$10.76}{1000\ c.f.}\right)\left(\frac{1\ hour}{42\ tons}\right) = \frac{\$2.386}{ton\ DDGS}$$

The total cost of pelleting can now be determined by adding together equipment costs, labor costs, replacement costs, electrical costs, and steam generation costs:

| | |
|---|---|
| Equipment costs: | \$0.120/ton DDGS |
| Labor costs: | \$0.105/ton DDGS |
| Replacement costs: | \$0.144/ton DDGS |
| Electrical costs: | \$0.715/ton DDGS |
| Steam generation costs: | \$2.386/ton DDGS |
| | \$3.470/ton DDGS |

## Drying to 16% Moisture and Pelleting Without Conditioning

If the DDGS could be dried to only 16% moisture, it may be possible to pellet them directly. This would save on fuel costs both in drying and in pelleting, as less energy would be needed to dry to the higher moisture content, and no energy would be required for steam generation. DDGS would still be produced at approximately the same rate; to dry from 65% to 16% moisture the amount of water that would have to be removed can be calculated:

$$\frac{2.2x10^5\ lbs\ WDGS}{hour}(35\%\ DM)=\frac{x\ lbs\ DDGS}{hour}(84\%\ DM), x=\frac{9.0x10^4\ lbs\ DDGS}{hour}$$

This is equivalent to $1.26x10^5$ lbs of water removed (J). Based on the previously used equation, the amount of natural gas required is:

$$\frac{1.26x10^5 lbs\ water\ (J)}{hour}\left(\frac{1\ kg}{2.20\ lbs}\right)\left(\frac{0.06\ kg\ Natural\ Gas}{1\ kg\ water}\right)=\frac{3.4x10^3 kg\ Natural\ Gas\ (K)}{hour}$$

Again, using the previous equation, the following gives the cost per hour of drying:

$$\frac{3.4x10^3 kg\ N.G.}{hour}\left(\frac{2.2\ lbs}{1kg}\right)\left(\frac{21,548\ BTU}{1lb}\right)\left(\frac{1000\ c.f.}{10^6 BTU}\right)\left(\frac{\$10.76}{1000\ c.f.}\right)$$

$$=\frac{\$1756\ (L)}{hour}\ or\ \frac{\$41.82}{ton\ DDGS}$$

Because the DDGS would already be at 16% moisture, it would not be necessary to generate steam for conditioning. This would make the pelleting cost:

| | |
|---|---|
| Equipment costs: | $0.120/ton DDGS |
| Labor costs: | $0.105/ton DDGS |
| Replacement costs: | $0.144/ton DDGS |
| Electrical costs: | $0.715/ton DDGS |
| | $1.084/ton DDGS |

## Summary

| | Drying Cost ($/ton DDGS) | Pelleting Cost ($/ton DDGS) | Total |
|---|---|---|---|
| **Raw DDGS** | $43.72 | N/A | $43.72 |
| **Pelleted DDGS (Dry to 10%, condition to 16%)** | $43.72 | $3.47 | $47.19 |
| **Pelleted DDGS (Dry to 16%, no conditioning** | $41.82 | $1.08 | $42.90 |

It should be noted that the cost per ton for all values in the above table are based on a rate of 42 tons per hour of DDGS on a 90% DM basis, which would be the amount produced with no processing changes. This is done for the sake of relative comparison. However, pellets coming off a pellet cooler would likely be closer to 12% meaning a higher overall production rate of DDGS ≈ 43 tons per hour. Also, the DDGS dried to 16% moisture and pelleted may lead to lower costs per ton produced because of added water. These factors, as well as others, may slightly change the cost per ton of DDGS produced.

# Literature Cited

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