ABSTRACT

POPE, JEFFREY TAYLOR. Alternative Methods in Feed Manufacturing Affecting Pelleting Parameters and Broiler Live Performance. (Under the direction of Dr. Adam C. Fahrenholz).

A series of experiments was conducted utilizing unconventional practices in feed manufacturing to include coarse particles in broiler diets and to improve pellet durability. The first experiment examined the effects of three particle sizes of corn and two different pellet diameters on feed manufacturing and broiler live performance from 16 to 41 d of age. After feeding a common fine corn starter (FC), the milling and diet treatments continued with either all FC, 31% of the diet as coarse corn (CC), or 10% of the diet as whole corn (WC) pelleted through either a 3.5 or 4.4 mm die.

The 41 d FCR was not affected by corn particle size, although FC diets exhibited improved FCR during early stages of growth. The larger 4.4 mm pellets improved FCR at 41 d and during the 14-27 d and 35-41 d periods. It was concluded that pre-pelleting WC could be used as an alternative to adding CC to diets, and that CC does not negatively affect broiler live performance.

A second experiment examined the effects of two fat application sites and two levels of percentage fines when fed from 16 to 44 d of age on feed manufacturing, broiler live performance, and carcass yield. Birds were fed a common crumbled broiler starter before transitioning onto one of five dietary treatments. The experiment was a randomized complete block 2 x 2 design with one additional treatment to study the effect of pellet quality entering a post-pellet liquid application (PPLA) system. The fat application sites included mixer added fat (MAF) and PPLA. The percentage fines utilized were 0 and 30%. Thus, there were initially 4 treatments MAF-0%, MAF-30%, PPLA-0%, and PPLA-30%. With the PPLA-30% treatment two mixing methods were used to generate a fifth treatment. One PPLA-30%

treatment had fat added to a mixture of pellets and fines while the fifth treatment had fat partitioned to the pellets and fines separately before recombining to make the complete diet. At 44 d, two males and two females that represented the house average BW for each sex were selected from each pen for carcass yield.

PPLA fines exhibited significantly more energy and crude fat as compared to PPLA pellets. Males consuming PPLA diets exhibited improved BW at 28, 35, and 42 d. PPLA diets improved FCR at 28, 35, and 42 d. Females consuming PPLA-30% diets were significantly heavier than females consuming MAF-30% diets at 28 and 35 d. It was concluded that the fat laden fines in the PPLA-30% diet improved female BW when compared to the MAF-30% diet.

A third series of experiments were conducted to determine the ability of lignosulfonate to improve pellet durability index (PDI) in marginal pelleting conditions. The marginal pelleting condition utilized in the first trial was temperature. Feed was pelleted with and without 0.5% lignosulfonate over a range of temperatures from 160 to 180 °F. An interaction effect was observed in which lignosulfonate improved PDI more at lower temperatures than at high temperatures. The second trial utilized two percentages of MAF (1.5 and 3.0%), two particle sizes of corn (FC and CC), and two percentages of lignosulfonate (0 and 0.5%). Lignosulfonate improved PDI by 22 points in 3.0% fat diets, but only 11 points in 1.5% fat diets. The third trial examined the effect of lignosulfonate over a range of dietary crude protein from 16 to 24%. The addition of lignosulfonate resulted in an equivalent improvement in pellet durability at each level of crude protein. It was concluded that lignosulfonate was able to improve PDI in certain marginal pelleting conditions, such as low pelleting temperatures and high fat inclusion.

Alternative Methods in Feed Manufacturing Affecting Pelleting Parameters and Broiler Live Performance

by
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DEDICATION

I would like to dedicate this work to my wife, family, and friends. You drive me everyday to make the best of each opportunity. Without you, I have nothing.

BIOGRAPHY

Jeffrey Taylor (J.T.) Pope was born on March 30, 1991 to Nancy Jo Richards and Jeffrey Boyd Pope in Chapel Hill, NC. He grew up in Hillsborough and Mebane, NC. His parents were hardworking and dedicated to providing the best possible childhood for their son. He loved to play baseball and football, and was very dedicated to being an athlete until adulthood. While neither of his parents came from agricultural backgrounds or worked in an agricultural industry, growing food always fascinated him. When he was an early teen, his father bought a new home with resident poultry that became his responsibility. He grew to love his daily chores, and often wondered why the feed store sold pelleted and mash feed. Little did he know, a large portion of his time would later be dedicated to answering that very question. After playing a year of collegiate baseball elsewhere, JT would attend North Carolina State University to pursue a Bachelor of Science in Poultry Science. While an undergraduate, he worked at the university feed mill and chicken research unit as a research assistant. He graduated from NCSU in May of 2014, started work towards a degree in Pharmacy but soon returned to NCSU to pursue a Master of Science in Poultry Science.

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I am forever grateful for my parent's selfless approach to raising me and for providing the best of childhoods that anyone could imagine. Finally, thanks to my wife, Amber. I know everything is going to be fine at the end of the day, for I have you. That gives me more strength than you could ever imagine, and I love you dearly.

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ABBREVIATIONS

BW	Body weight
FI	Feed intake
FCR	Feed conversion ratio, adjusted for mortality
PDI	Pellet durability index
F	Fahrenheit
C	Celsius
kg	Kilogram
g	Gram
m	Meter
µm	Micrometer
d	Day
kWh/T	Kilowatt-hours per ton (U.S.)
ΔT	Change in temperature
E	Embryonic day
N	Newton

LITERATURE REVIEW

The Benefits of Pelleting

Feed is most commonly offered to animals in two forms; mash or pellets. Mash feeds are manufactured by blending ground ingredients into a uniform mixture. The particles in mash feed remain free to migrate throughout the mixture since no step has been taken to bind the individual particles. Pelleting, an additional processing step that is optional, binds the ingredients of the mixture into a cylindrical shape that fixes ingredients in place through the inherent binding properties of the ingredients when they are subjected to heat treatment and pressure within a pelleting die.

The benefits of pelleting have been apparent to feed manufacturers as well as poultry producers for many years. The benefits of pellets, from a material handling perspective, have included improved flow, increased bulk density, and reduced segregation during transportation (Thomas & van der Poel, 1996). Improved flow properties have been associated with decreased bridging in feed storage bins. Improved bulk density resulted in less space needed to store feed and decreased time spent loading and unloading the feed from the feed mill to the farm. Reduced segregation not only prevented loss of material as it passed through unenclosed transitions, but also prevented selective feeding and ensured delivery of each ingredient as the formulation intended.

From a bird performance perspective, pellets have been proven to be very beneficial. Jensen *et al*. (1962), in a basic feed form study comparing mash diets to pelleted diets in chickens and turkeys, drew conclusions touting the importance of pellets. Poults fed mash spent almost 19% of their day consuming feed, while those fed pellets consumed feed only 2.2% of the day. While chicks were less susceptible to the differences in feed form, they still consumed more efficiently when fed pellets compared to mash feed. The chicks consumed feed for 14.3% of their day when fed mash feed compared to 4.7% of the day when eating pellets. The reduction in time spent eating was associated with increased energy expenditure being available for growth instead of prehension.

The Benefits of High Quality Pellets

After the benefits of pelleted feeds were established, there was a need to determine how pellet quality affected live performance. Pellet quality has been defined as the ratio of pellets to pellet fines in the feeder (McKinney & Teeter, 2004). Pellet fines, as a representation of pellet quality, can be measured in the feeder on the farm, or at the feed mill. As a predictor of pellet quality, pellet durability may be determined by stressing pellets through various testing methods that mimic feed mill to farm conveyance. Two common methods used to predict pellet durability have included the tumble box method (ASAE S269.4) and the Holmen pellet tester (TekPro, United Kingdom). The tumble box method uses mechanical disintegration that mimics the conveyors and augers typically used in the United States to deliver pelleted feed to farms. The Holmen pellet tester uses pneumatic disintegration, which better mimics feed delivery systems found in Europe.

Thomas & van der Poel (1996) explained that attrition stress in poor quality pellets subjected to conveying equipment resulted in a higher incidence of fines. Two types of stress were associated with producing fines. Fragmentation was defined as the fracture of pellets into smaller particles and fines. Abrasion, the fracture of the edge or surfaces of pellets, was the other stress that generated fines.

In a study analyzing the effect of pellet-to-fines-ratio, Mckinney & Teeter (2004) determined that decreasing pellet quality resulted in a linear decrease in body weight (BW) gain and poorer feed conversion ratio (FCR). The effect of pellet quality on live performance was attributed to the effective caloric value of the feed. High quality pellets required less energy to consume because they were easier for the bird to grasp. Conversely, pellets with a high incidence of fines required more energy expenditure for prehension because they were more difficult to grasp and required the bird to spend more time at the feeder, effectively reducing the caloric density of the feed.

Proudfoot & Hulan (1982) fed turkeys diets containing varying levels of fines, as well as a mash feed to act as a control. They concluded that feeding a combination of pellets and fines led to improved BW and FCR when compared to feeding mash. Proudfoot & Sefton (1978) conducted a similar study with broilers, feeding different levels of fines and a mash diet as a control. They found that broilers fed up to 45% fines exhibited improved BW and FCR when compared to a 100% fines diet. Notably, an inverse correlation was established between monetary returns, calculated based on live performance and carcass yields, and percentage fines.

Several other studies have also demonstrated the benefit of high quality pellets. Feeding 80% pellets, as opposed to 50% pellets, resulted in 8 points of FCR improvement and 0.17 pounds of BW improvement in broilers (Wamsley & Moritz, 2014). When comparing pellets of high, medium, and low quality to ground pellets, Lilly *et al*. (2011) concluded that high and medium quality pellets resulted in increased FI and BW gain when compared to low quality pellets and ground pellets. In addition, a pellet in any form improved FCR when compared to ground pellets. Other reasons for enhanced performance due to quality pellets have included increased palatability and decreased ingredient segregation (Behnke, 2001).

Offering broilers high quality pelleted feed altered their behavior patterns. When presented with high quality pellets, broilers increased their resting frequency and decreased their eating frequency (Skinner-Noble *et al*., 2005). Improved pellet quality was associated with an increased net energy for a broiler. The energy required to consume a diet must also be considered during formulation. If a diet was formulated with factors knowingly attributing to poor pellet quality, it should be expected that delivery of net energy to a broiler will suffer because the energy associated with prehension would increase.

It has also been well established that dominant birds monopolize feeder space (Nakaue, 1981; Quart & Adams, 1982; Cunningham *et al*., 1988; Glover *et al*., 2016). Birds have been reported to compete for resources, especially in large groups (Leone & Estevez, 2008). Birds have been found to arrive at feeders at different times and remain there for different amounts of time. Most often, the dominant birds were the largest birds (Nakaue, 1981; Glover *et al*., 2016). It has also been established that pellets and fines were not entirely consistent in nutritional composition (Cutlip *et al*., 2008). If pellet quality was not controlled, there could be differences in the nutritional composition of feed and the net energy afforded, based on hierarchy and feeding dominance between birds.

High quality pellets may also improve distribution of liquid ingredients post-pelleting. Fines have an increased surface-area-to-mass ratio relative to whole pellets. When applying a liquid ingredient post-pellet, there should logically be potential for the fines to receive more than their equal proportion by weight of the liquid ingredient since they have a large surface area, but a small mass. Hinting to this theory, Wamsley (2014) reported different results in phytase recovery based on liquid application site after augering diets through a conventional broiler grow-out house. While mixer added phytase concentration consistently decreased as the feed was augered through a 200-foot house, the post-pellet added phytase experienced an increase in concentration to 51-feet, a decrease from 51-146-feet, then an increase from 146-191-feet. The inconsistency displayed could be result of poor uniformity in liquid application method, or poor uniformity in liquid absorption because of different sized particles.

Also of interest, Cutlip (2008) found that sifted pellets retained 1% more moisture than fines even though they did not differ in protein or ash content. During the cooling process, the increased surface-area-to-volume ratio would cause smaller particles to lose more moisture. The decreased moisture of fines would cause an increased affinity and holding capacity for liquid relative to their larger counterpart. This was especially true in the case of hydrophobic substances, such as poultry fat, because the hydrophobic effect weakened as the moisture was reduced which would allow fat to more easily coat fines.

Factors Affecting Pellet Quality and Pelleting Cost

Several factors in the feed manufacturing process have been identified that affect pellet durability outcomes, which in turn affect generation of fines. These factors include ingredient composition, conditioning, particle size, die specification, and cooling (Behnke, 2001). Stark & Ferket (2011) added that pellet mill throughput was also a factor that must be considered when controlling pellet quality. Wood (1987) demonstrated that increasing the gelatinized-starch-to-native-starch ratio led to an increase in pellet durability. Briggs *et al*. (1999) concluded that increasing protein content when formulating feed led to increased pellet durability. Investigating the benefits of starch and protein, Buchannan & Moritz (2009) added cellulose and soy protein isolate to typical corn-soy diets. Adding either ingredient at 5% inclusion increased pellet quality by at least 7 points, decreased fines generation, and increased the consistency of quality pellets. Starches and proteins, as part of diet formulation, have a beneficial effect on pellet quality. Also affecting pellet quality as a part of feed formulation has been the amount and location of liquid fat addition. Increasing mixer added fat, or fat added pre-pelleting, decreased pellet quality (Gehring *et al*., 2011; Fahrenholz, 2012; Wamsley *et al*., 2013).

To take advantage of the binding qualities of starches and proteins, these nutrients must first be subjected to steam conditioning. Adding water and heat over a period of time prepared feed ingredients for compaction as they passed through a pellet die. Steam addition in the conditioner has been used to add moisture and heat to the conditioning process. The increased temperature and moisture activated physical and chemical property changes leading to the gelatinization of starches and denaturation of proteins (Thomas *et al*., 1997). Stark (1994) demonstrated that increasing the temperature of mash feed exiting the conditioning chamber through increased addition of steam resulted in improved pellet durability. Increasing the pressure at which steam entered the conditioning chamber also increased pellet quality attributable to the increased enthalpy of higher-pressure steam (Cutlip *et al*., 2008). Even though increasing conditioning temperature and steam pressure would seem to be detrimental to nutrient preservation during the pelleting process, neither variable negatively affected amino acid digestibility or metabolizable energy (Cutlip *et al*., 2008). Gilpin *et al*. (2002) indicated that increasing retention time also increased pellet durability.

Die specifications have also played an important role in the manufacture of quality pellets. Increasing the length-to-diameter ratio of the die hole resulted in increased contact surface of feed with the die. Stark & Ferket (2011) demonstrated that increasing the length-to-diameter ratio of the pellet die resulted in increased pellet durability. Another controllable factor involving the pellet die was the distance between the pellet mill rolls and the face of the die where the “feed pad” was formed. To an extent, increasing the gap between rolls and the die face increased pellet durability, and then pellet durability decreased as the gap increased beyond an optimum point (Payne, 1979; Robohm *et al*., 1989).

Cooling pellets also affected their resulting quality. Coolers can be adjusted to run different feed bed depths, utilize different volumes of incoming air per unit time, and depend greatly on ambient air quality used to cool the pellets. Also affecting pellet quality, as mentioned by Stark & Ferket (2011), was the rate at which pellets were produced. An inverse relationship existed between pellet durability and pellet production rate.

Currently, feed represents the greatest monetary input for animal producers. It has been estimated that 60 to 70% of the cost of animal production was dedicated to feed ingredients and their transition into an edible form (McKinney & Behnke, 2007). The greatest expenditure in the manufacture of broiler feeds was the pelleting process, which represented over 40% of the energy consumed in feed mills (Whitehead & Shupe, 1980). In some instances, the pellet mill alone consumed over half of the energy required to get raw ingredients into a finished feed form.

Since feed mills associated with integrated broiler producers have been viewed as a cost center, every effort has been made to reduce monetary inputs because the mill was not directly accountable for any profits. Feed mills should always be operated at their maximum capacity or their resources will be under utilized. In many instances, feed mills have been asked to produce feed over their maximum capacity to keep up with demands of the processing plant. Because feed mills were a cost center and often operated at or above their maximum capacity, several measures were taken to reduce the cost to manufacture feed and increase the rate at which the feed was produced. Since the pellet mill consumed the most energy in the feed manufacturing process, it was the piece of equipment that had the most opportunity for improvement when considering cost reduction. Factors known to decrease the overall operating cost of pellet mills have included increasing throughput, increasing mixer added fat, increasing conditioning temperature, and reducing the pellet die length-to-diameter ratio.

Holding all factors affecting pellet production rate constant, other than throughput, Stark & Ferket (2011) demonstrated that pellet mill efficiency was improved as pellet mill production rate increased. When production rate was at its greatest, the pellet mill produced more kg of feed per horsepower hour (kg/hphr). Also well known to decrease electrical costs of pelleting was the addition of mixer added fats. Energy consumption was reduced by 1.44 kWh/metric ton by including 4% mixer added fat as opposed to 1% mixer added fat (Gehring *et al*., 2011). In a similar study, Corey *et al*. (2014) reported a 1.4 unit savings in kWh/metric ton by increasing mixer added fat by 2%. The additional fat in the diets lubricated the die cylinder and decreased the friction between the die cylinder surface and the particles composing the diets.

Increasing the conditioning temperature, when feed formulation allowed, also reduced energy consumption and increased throughput at the pellet mill. Loar *et al.* (2014) observed a decrease in energy consumption at the pellet mill as the temperature of the conditioned mash increased. Briggs (1999) *et al.* concluded that increasing the residence time of mash in the conditioner, by changing conditioner pick angles or using a longer conditioner, increased pellet durability by up to 4.5 points.

Another factor at the pellet mill that reduced costs was pellet die specification. Stark & Ferket (2011) pelleted diets composed of the same ingredients through pellet dies having different length-to-diameter ratios. As the length-to-diameter ratio of the pellet die increased, pellet mill energy consumption increased. The increased length of contact between the pellet die and conditioned mash led to increased friction, resulting in increased energy required to push feed through the die. Most of the aforementioned factors that integrators have utilized to save money at the pellet mill also impacted pellet quality and subsequent bird live performance. Other than increased conditioning temperatures and conditioning time, the factors that have been adjusted to save money at the pellet mill have generally negatively impacted pellet quality and resulting bird live performance.

Particle size, mentioned by Behnke (1994) as another factor affecting pellet quality, has followed a consistent trend throughout the literature. With few exceptions, smaller particle size diets made better pellets (Reece *et al*., 1986; Wondra *et al*., 1995; Chewning *et al*., 2012). Smaller particles, from a live performance perspective, were associated with an increased surface area for exposure to digestive enzymes while decreasing mastication energy requirements (Amerah *et al*., 2008). Animal producers often fine grind as much of the diet as possible.

Coarse Particles in Feed Manufacturing and Broiler Performance

While coarse particles of grain have been believed to negatively impact pellet quality and reduce the surface area exposed to digestive enzymes, several researchers have found that pellet quality was only minimally impacted by coarse ground grain and furthermore found them beneficial in poultry diets. Increasing the particle size of corn has been generally accompanied by a decrease in the cost to grind the corn. Reece *et al.* (1986) demonstrated that an increase in the screen opening on a hammer mill was associated with an increased grinding rate while energy input remained constant. Approximately 25 to 30% of feed manufacturing costs were associated with energy use (Whitehead, 1980), with the reduction of particle size being the second most expensive process in a feed mill (Reece, 1985). Supplementing a portion of the broiler diet with a coarser ground grain reduced energy costs.

While it was generally accepted that increasing corn particle size decreased pellet quality (Angulo *et al*., 1996), there were cases where particle size had little to no effect on pellet quality and subsequent broiler live performance. Progressively increasing the amount of rolled corn in broiler grower diets, up to 35%, was shown to decrease electrical cost at the hammer mill and pellet mill without adversely affecting cumulative broiler live performance through the finishing period (Dozier *et al*., 2006). Pellet quality was shown to increase as pre-pelleting inclusion of whole corn increased (Singh *et al.*, 2014), while adding coarser particles through increasing screen hole diameter on a hammer mill produced no effect on pellet quality in another study (Amerah *et al*., 2008). From a feed quality perspective, and in disagreement with several other publications, there was evidence that supplementing coarse grain in amounts that would be beneficial to poultry gastrointestinal tract function would not detrimentally impact pellet quality.

Understanding the avian digestive tract has become paramount to realizing the benefit of coarse particles in poultry diets. The avian digestive tract has been shown to be unique with respect to other domesticated animals in that it contains a mechanical stomach, or gizzard, caudal to the glandular stomach, or proventriculus. This allows avian species to make considerable alterations in the particle size of components of the digesta before it enters the absorptive portions of the gastrointestinal tract. Avian species have ground all particles in the digesta to a minimum size before allowing it to pass into the small intestine (Clemens *et al*., 1975; Moore, 1999). Research has shown that as the gizzard contracted, it moved material down the digestive tract (peristalsis), or returned material back to the glandular stomach (reverse peristalsis) for increased exposure to acidic secretions and activation of enzymes to increase nutrient digestion (Duke, 1992).

Development of the gizzard was reported to commensurate with the particle size of the diet (Biggs & Parsons, 2009). As the particle size of diets increased, the volume of diet contained within the organ increased more than the weight of the organ (Hetland *et al*., 2003). The fullness and capacity of the gizzard played a crucial role in satiety signaling (Denbow, 1994), which ultimately affected motility of digesta through the gastrointestinal tract. A full and stimulated gizzard slowed the movement of digesta through the gastrointestinal tract, which afforded more time for absorption of nutrients (Ferket, 2000).

The benefits of adding coarse particles to broiler diets have been well documented. The main benefits associated with added coarse particles included improved FCR, increased or sustained BW, and increased nutrient utilization that have been related to increased gizzard function. Xu *et al.* (2015) successfully demonstrated that increasing the inclusion of coarse corn in a corn-soy diet to 25 or 50% resulted in improved FCR and increased BW by up to 8 points and 189 g at 42 d, respectively. Similar results have been observed in studies evaluating differences in wheat-based diets. Singh *et al.* (2014) concluded that adding whole wheat pre-pellet or post-pellet in substitution for ground wheat resulted in improved FCR by up to 30 points between 11 and 35 d of age. Other similar studies have concluded that increased particle size of corn, wheat, or soybean meal did not have a significant effect on FCR (Amerah *et al*., 2008; Pachecho *et al*., 2014).

Increasing the size and inclusion rate of coarse particles stimulated gizzard function and proliferation. Increasing the particle size from 300 to 600 μm in pelleted and mash diets increased gross and relative gizzard weights in both feed forms (Chewning *et al*., 2012). When including coarse corn at 0, 25, and 50% of total corn, gross and relative gizzard weights increased in a linear manner (Xu *et al*., 2015). Well-developed gizzards were associated with decreased particle size of digesta, which inherently increased nutrient utilization by increasing the surface area of particles exposed to digestive enzymes (Svihus, 2011). A gizzard stimulated by coarse particles exhibited slowed gut-passage rate, and increased amount of time digestive enzymes were exposed to digesta. This effectively improved nutrient utilization, resulting in improved live performance. While the benefit of coarse particles in poultry diets has been well documented, no overwhelming consensus has existed for the optimum particle size and inclusion rate of coarse particles. The benefits of coarse particles have been generally recognized when improved nutrient utilization and slowed gut-passage rate overcame the energy invested in the growth and function of the gizzard and associated intestinal smooth muscle.

Improving Pellet Quality

As previously mentioned, adding fat to diets before pelleting has lubricated the interface of the conditioned mash with the interior of the die hole resulting in decreased energy expenditure to manufacture the same amount of feed (Ghering *et al*., 2011; Corey *et al*., 2014). Also previously mentioned were the typical detrimental effects that saving energy and increasing throughput at the pellet mill had on pellet quality, and how mixer added fat influenced both parameters.

A general rule of thumb has been that increasing the inclusion of mixer added fat caused a decrease in pellet durability. Loar *et al*. (2014) reported a 13-point gain in pellet durability index (PDI) by reducing the amount of mixer added fat from 2.18% to 1.0%. Gehring *et al*. (2011) demonstrated that increasing mixer added fat from 1% to 4% resulted in a 33-point decrease in PDI. They concluded that a diet with a greater amount of mixer added fat would be less able to withstand current industry handling practices where feed was augered through every point before the bird consumed the feed. Hott *et al*. (2008) explained that decreasing mixer added fat induced increased starch gelatinization due to increased friction between the die and conditioned mash, which resulted in increased pellet quality. A simple way to improve pellet durability was to withhold fat prior to pelleting, and then add the fat as a post-pellet liquid application to meet the formulated fat inclusion.

While mixer added fat was detrimental to pellet quality, it has been shown to have positive impacts on bird performance. Loar *et al*. (2014) concluded that pre-pellet fat alleviated nutrient destruction at higher conditioning temperatures because of its lubrication properties. Corey *et al*. (2014) also concluded that mixer added fat maintained digestibility of heat sensitive nutrients. Increasing mixer added fat decreased the frictional heat gained between conditioned mash and extruded pellets, again because of its lubrication properties. This had potential implications when adding heat sensitive ingredients, such as some enzymes or whey products.

Another way to alleviate poor pellet quality was through the addition of a pellet binder. A common pellet binder used in the feed industry has been lignosulfonate. It can be added as a salt of calcium, ammonium, or sodium (Acar *et al*., 1991). Lignosulfonates have been developed as surface acting agents with amphiphatic properties due to the hydrophobic nature of the aromatic benzene base combined with several oxygen atoms found in attached hydroxyl groups that were free to hydrogen bond, giving the compounds a hydrophilic nature as well (Ouyang *et al*., 2006). The duality of this molecule allowed it to penetrate the hydrophobic layer created by fat inclusion to increase binding at the surface of the pellet with other molecules that can hydrogen bond, such as proteins and carbohydrates, to increase the hardness of the surface of pellets. Lignosulfonate was described as a co-product of pulpwood manufacturing that contained lignin (Wang *et al*., 2012). Lignin is found in the cell walls of plants, giving them rigidity and stability. Lignosulfonate is also water-soluble, allowing addition at the mixer in liquid or powder form.

The ability of lignosulfonate to improve pellet durability has been well documented. Several publications have demonstrated lignosulfonate's ability to make more durable pellets (Pfost, 1964; Wamsley & Moritz, 2013; Corey *et al*., 2014; Wamsley & Moritz, 2014; Winowiski, 2015). More durable pellets have resulted in a lower incidence of fines, which was beneficial for live performance (McKinney & Teeter, 2004).

In early research of lignosulfonate's effect on live performance, Morrison *et al*. (1968) concluded that lignosulfonate could be fed to broilers at an inclusion rate of 4% without negatively affecting live performance. When fed over 4%, diuresis was reported and live performance suffered as a result. In a later study, Acar *et al*. (1991) revealed that lignosulfonate addition before pelleting increased the amount of material retained on a 4750 μm sieve, but did not alter broiler live performance.

Lignosulfonate has also been reported to improve nutrient utilization. Wamsley & Moritz (2013) demonstrated lignosulfonate's ability to improve the digestibility of several amino acids. The proposed mechanism by which lignosulfonate was able to spare amino acid digestibility was through decreased compression and frictional heat gain in the pellet mill die. In a following study, Wamsley & Moritz (2014) suggested that lignosulfonate addition in combination with fat could result in more stable emulsions, thereby allowing poultry to better utilize fat in feed. Based on the suggestions of previous publications, there was reason to believe that lignosulfonate could improve nutrient utilization while reducing fines generation, although little live performance data existed to back these claims.

An interesting interaction between pelleting parameters existed in which one beneficial factor, such as a high pelleting temperature, often negated another negative factor, such as high inclusions of mixer added fat, with respect to pellet quality. Loar *et al*. (2014) demonstrated this principle by pelleting diets at different temperatures with different inclusions of mixer added fat. When pelleting at a low temperature, 1% fat diets resulted in a 19-point improvement in PDI over 3% fat diets. When pelleting at a high temperature, 1% fat diets only improved PDI by 3 points over 3% fat diets. Lignosulfonate could be used as a tool to offset the negative impact afforded by other pelleting factors. For example, lignosulfonate inclusion improved pellet durability more in a high fat inclusion diet than in a low fat inclusion diet (Wamsley & Moritz, 2013). Lignosulfonate was also said to improve pellet mill throughput while reducing pellet mill energy consumption (Winowiski, 2012). Addition of lignosulfonate to poultry diets could potentially serve a dual role to improve feed manufacturing through increased pellet quality and decreased energy consumption while also improving broiler live performance through improved pellet quality and increased nutrient digestibility.

Hypotheses and Research Objectives

There has been a constant desire to reduce feed costs in the integrated broiler industry since feed mills represented a cost center that could not be directly accountable for profits. Some of the most common ways to reduce feed costs have been through improving the efficiency of the feed manufacturing process and least cost formulation of diets. While the feed mill was considered a cost center, it was important to realize that the way feed was made had a profound impact on broiler live performance.

Particle size and pellet quality were two of several factors known to directly impact broiler live performance as result of feed manufacturing methods. Pellet mill die specifications have also been shown to have an impact of broiler live performance. Adding CC to poultry diets was demonstrated to improve FCR (Singh *et al.,* 2014, Xu *et al.,* 2015). The CC was substituted into poultry diets through various methods. These most often included the use of roller mills or adjusted parameters of hammer mills, such as screen size or tip speed, to generate a coarse grind. A less common method to include CC in broiler diets included adding pre-pelleting whole corn (Singh *et al.,* 2015). Creating the CC effect through the inclusion of pre-pelleting whole corn could give poultry producers an alternative method to introduce CC if the infrastructure, such as a roller mill or a hammer mill with an adjustable tip speed, was not available to introduce CC.

As demonstrated by McKinney & Teeter (2004), maintaining good pellet quality was imperative to the successful rearing of broilers. There were several factors affecting pellet quality, described by Behnke (2001), but the most influential factor was ingredient composition. Mixer added fat was detrimental to pellet quality (Auttawong, 2015), so post-pellet liquid application systems were implemented in feed mills to reserve the ability to add fat to poultry diets after the pelleting process. This allowed pellet quality to be maintained while meeting the energy requirements of broilers. Another formulation factor that was able to alleviate poor pellet quality was lignosulfonate. Lignosulfonate was able to improve pellet durability in diets with large quantities of mixer added fat (Wamsley & Moritz, 2013). It has also been demonstrated that smaller diameter pellets were more suitable for broilers, with respect to FCR, during the 15-35 d period (Fahrenholz *et al.,* 2013). The focus of this thesis was to determine if alternative methods of supplying CC, high quality pellets, and pellets differing in diameter would be adequate to maintain broiler live performance relative to more conventional methods.

Chapter I Hypotheses and Objectives

It was hypothesized that the addition of pre-pelleting WC would not impact energy consumption at the pellet mill, and that it would offer an alternative to adding CC to broiler diets to improve FCR. It was also hypothesized that a smaller diameter pellet would be more suitable for broilers before 35 d of age. The objective was to determine if feeding smaller diameter pellets would allow the FCR benefit of coarse particles to be realized before 42 d of age.

Chapter II Hypotheses and Objectives

It was hypothesized that removing fat prior to pelleting would increase energy consumption at the pellet mill and improve pellet durability when compared to a diet in which all the formulated fat remained in the mash feed prior to pelleting. In addition, it was hypothesized that adding post-pellet fat to a diet with a high incidence of fines would result in more absorption of fat by the fines when compared to pellets. It was also hypothesized that a diet composed of 30% fines would negatively impact live performance when compared to a diet free of fines. The objectives were to determine whether fat preferentially coated fines or pellets in a PPLA system, and to determine what impact it might have on broiler live performance.

Chapter III Hypothesis and Objectives

It was hypothesized that addition of lignosulfonate would alleviate poor pellet quality in marginal conditions known to induce poor pellet quality. The marginal conditions included aspects of feed formulation, mash conditioning, and mash particle size. The objective was to determine under which conditions lignosulfonate would be most effective and beneficial to add to diets.

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CHAPTER I

EFFECT OF WHOLE CORN AND PELLET DIAMETER ON FEED MANUFACTURING PARAMETERS AND BROILER LIVE PERFORMANCE FROM 16 TO 41 DAYS OF AGE

Introduction

Xu *et al.* (2015) demonstrated that broilers consuming CC exhibited improved FCR at 42 and 49 d. The addition of CC resulted in increased reverse peristalsis, which allowed broilers to better utilize nutrients. While many studies have proven coarse particles of grain to be beneficial to broiler FCR, the benefit was only realized beyond 35 d in most instances. It was also demonstrated by Singh *et al.* (2014) that pre-pelleting inclusion of whole corn (WC) could stimulate the gizzard, just as CC was shown to in previous particle size studies.

Fahrenholz *et al.* (2013) demonstrated that offering broilers a 3.5 mm pellet, when compared to a 4.4 mm pellet, resulted in improved FCR during the 15-35 d period. Offering broilers a smaller diameter pellet could potentially allow the FCR benefit of adding CC or WC to broiler diets to be realized at or before 35 d of age.

Materials and Methods

Feed Manufacturing

The experimental design was a 2 x 3 randomized complete block utilizing three particle sizes of corn and two pellet diameters. The broilers were fed a common fine corn (FC) starter crumble then transitioned onto one of the six dietary treatments at approximately 16 d of age. The grower diets contained all-fine corn inclusion, 31% of diet added as coarse corn, or 10% of diet added as whole corn. The chosen amount of CC inclusion was based on previous studies that demonstrated the positive effect of CC on broiler FCR. The WC inclusion amount was chosen to mimic the CC inclusion to attempt to generate mash diets similar in particle size. The pellet diameters utilized for the grower diets were 4.4 and 3.5 mm.

All feed was manufactured at the North Carolina State University Feed Mill Educational Unit following the guidelines for current Good Manufacturing Practices (cGMP). All FC was ground through a hammer mill (Model 1522, Roskamp Champion, Waterloo, IA) containing a pair of 2.4 mm screens. All CC was ground through a double pair roller mill (Model C128889, RMS, Sea, SD) with a top gap setting of 55% open and a bottom gap setting of 35% open. The diets were batched and then blended in a counterpoise ribbon mixer (Model TRDB126060, Hayes & Stolz, Fort Worth, TX) for 180 seconds of dry mix followed by an additional 90 seconds of wet mix. The diets were conditioned for 30 seconds at 175°F in a single pass conditioner (Model C18LL4/F6, California Pellet Mill, Crawfordsville, IN) then pelleted using a 30 HP California Pellet Mill (Model PM1112-2, Crawfordsville, IN). The pellet mill was equipped with a 4.4 x 35 mm die for the starter diet and half of the grower treatments, or a 3.5 x 28 mm die for the remainder of the grower treatments. Pellets were cooled in a counter flow cooler (Model VK09X09KL, Geelen Counterflow USA, Inc, Orlando, FL). The starter diet was crumbled (Model 624S, Roskamp Champion, Waterloo, IA), while the grower diets remained in pellet form.

All grower diets were manufactured over a two-day period. The grower diet pelleting sequence was randomized into two groups based on pellet diameter, pelleting 227 kg per run. All of the 3.5 mm diameter pellets were manufactured on the first day, while the 4.4 mm diameter pellets were manufactured on the second day. Each treatment was replicated three times for a total of eighteen runs, which produced six replicates per corn particle size treatment and nine replicates per pellet diameter treatment.

Incubation

Sixteen trays containing 180 eggs each, one tray from each 51-wk-old breeder pen, were placed in Jamesway incubators. The eggs were preheated for 12 hours at 80°F and then brought to 100.5°F setpoint with a wet bulb of 85°F. The exhaust vent was closed at set. As incubation continued, the exhaust vent was progressively opened. At E4, the setpoint decreased to 99.5°F while maintaining a wet bulb of 83°F. On E12, dry bulb temperature was decreased and ventilation increased accordingly to maintain an internal egg temperature of 100°F.

Grow-out

The rearing of broilers occurred at the North Carolina State University Chicken Educational Unit in the East end of House 1. A total of thirty-six 1.2 x 3.8 m pens were used, allotting six replicates per dietary treatment. Each pen contained one bell-type drinker and two tube feeders. Each pen was top dressed with fresh shavings prior to placement.

A total of 576 Ross 708 males were allocated to one of six dietary treatments. Upon hatching, each chick was feather sexed and kept separate based on hatching tray and breeder pen. Sixteen chicks, one from each breeder treatment, were randomly selected to be neck tagged for identification, group weighed, and placed in a pen. Selecting one chick from each hatching tray equalized any effect that breeder treatment may have imposed upon progeny. Each chick was introduced to water and placed on feed upon entering the pen. Chicks were observed for crop fill within two hours of placement.

Three supplemental feeding trays and one supplemental drinker were in each pen upon chick placement. Supplemental feeding trays were removed at 7 d, 10 d, and 13 d. All feed was screened to exclude litter before removing the third tray at 13 d, and added back to a tube feeder. Each chick was allotted 908 g of common FC starter crumble. At 13 d, with starter crumbles still in the feeder tube, the dietary treatment grower diets were added to each pen. The estimated initiation of grower consumption was 16 d based on visual observation. The chicks were granted ad libitum access to feed throughout the entire trial. Fresh water was added to supplemental drinkers as needed based on water levels and quality during the first 7 d.

The house was checked twice daily to record maximum and minimum temperatures and to check for any mortality. Thermostats, curtains, and ventilation were monitored and adjusted daily to achieve protocol objectives for temperature and air quality. Through 13 d, crumbled starter feed was added to supplemental feeders to give chicks access to fresh feed. From 7 d, each tube feeder was shaken daily and from 14 d each tube feeder was shaken twice daily. Drinkers were dumped to clear litter as needed based on water quality. At 7 d, chicks were counted to confirm mortality records. Feed was adjusted at 13 d for any mortality to ensure all birds had access to the same amount of starter feed prior to transitioning to treatment grower diets.

The lighting schedule was set to 23 h to 7 d, 22 h to 14 d, 21 h to 21 d, then approximately 14 h thereafter. The litter brooding temperatures were set to 97°F on placement before being decreased to 84°F in increments by 7 d. The temperature remained approximately constant at 83°F to 14 d, 80°F to 21 d, and finally 75°F through 41 d. Litter temperatures were measured using an IR gun.

Data Collection

Feed manufacturing data collection included production rates, conditioned mash and hot pellet temperatures, pellet samples for pellet durability analysis, and energy utilization.

One set of data was collected for each randomized 227 kg run, with three replicates allocated per dietary treatment. Production rates were converted to tons per hour by weighing a sample gathered over a 30 second time period during the middle of the run and then multiplying by 120 to get a ton/hour estimate. Immediately after taking the production rate sample, conditioned mash temperature was recorded via a thermocouple in the conditioner, and another pellet sample was collected in an insulated bucket probed with a thermometer to find the maximum pellet temperature for calculations of change in temperature between conditioned mash and hot pellets. A tray sample of pellets was collected and immediately cooled in a custom manufactured experimental cooler for eight minutes.

All pellets were subjected to pellet durability testing via the KSU tumble box standard and modified method as well as the Holmen (Model NHP100, TekPro, United Kingdom) method for 30 and 60 seconds. The KSU tumble box was custom manufactured in accordance with ASAE S269.4, and the same standard was followed for testing the durability of each replicate. All 3.5 mm diameter pellets were screened with a #6 US sieve, while the 4.4 mm pellets were screened with a #5 US sieve, in accordance with the standard. Samples of screened pellets without fines (500 g) were subject to the standard KSU tumble box method with only pellets in the tumbling chamber, as well as the modified KSU method that included three 19mm hex nuts with pellets in the tumbling chamber. After tumbling for 10 minutes, the pellets were screened by their respective sieves and weighed again to represent a proportion of the initial mass added to the tumbling chamber. The Holmen method was performed by weighing a 100 g sample of screened pellets using respective screens based on pellet diameter, then placing them in the air circulation testing chamber for 30 seconds and 60 seconds. Pellets were removed directly from the testing chamber and weighed after being subjected to testing to represent a proportion of the initial mass added to the testing chamber. Tissue paper was placed over the ventilation port to keep fines from exiting the testing chamber and the fines collection chamber was emptied after every other test.

Energy utilization data was collected by the feed mill's automation system (Model 47011, Repete, Sussex, WI). Energy consumption, collected as an input continuous variable at the programmable logic controller in HP, was recorded automatically every 15 seconds. The HP readings were separated by time for each replicate and then averaged over the entire run. The average HP consumption for each treatment was converted to kW/h and then coupled with the average production rate for each treatment to calculate energy consumption in kWh/ton.

Grower diet mash samples and ground corn samples were analyzed to determine particle size in accordance with ASAE S319.3. A split 100 g sample was placed in a sieve shaker (Model RX-29, W.S. Tyler Industrial Group, Mentor, OH) for 15 minutes accompanied by 0.5 g of silicone dioxide dispersion agent and sieve agitators.

Live data collection included group BW at placement, 13 d, 27 d, 34 d, and 41 d. Feed weighbacks were collected at 13 d, 27 d, 34 d, and 41 d. During 41 d BW collection, two birds per pen that represented the house average in BW were selected for proventriculus and gizzard weights. Each bird was euthanized via cervical dislocation, weighed, and proventriculus and gizzard excised. The proventriculus and gizzards were cleared of excess fat and contents, rinsed, blotted dry, and weighed.

The BW and feed weighbacks were used to calculate feed intake (FI) and feed conversion ratio (FCR). All FCR data was adjusted for mortality by adding the BW of any mortality from each pen into the FCR calculation. Period BW, FI, and FCR ratios were also calculated.

Data Analysis

The experimental design was a 2 x 3 factorial design with three different corn particle sizes and two different pellet diameters. Pelleting and live data were analyzed as a completely randomized block design using the GLM procedure of JMP 11.2 (SAS Institute, Cary, NC) for ANOVA. Means were separated via the LSMeans procedure of JMP and considered statistically significant at $P \leq 0.05$ unless otherwise noted.

Results

Feed Manufacturing Results

The composition of the common starter diet and the grower treatments are presented in Table I-1 and Table I-2, respectively. The particle size analysis results for corn and diet particle size are presented in Table I-3. The small mean diameter of the FC and the large mean diameter of the CC carried over into their respective broiler grower diets as the CC diets exhibited the greatest geometric mean diameter, the FC diets exhibited the smallest geometric mean diameter, and the WC diets represented an intermediate particle size in comparison to FC and CC diets.

The main effects of corn particle size and pellet diameter on pellet durability are presented in Table I-4. Corn particle size affected pellet durability utilizing the standard tumble box testing method. The WC diets approached significantly improved pellet durability ($P \leq 0.10$) compared to the CC diets, while the FC diets were intermediate. Pellet diameter also had an effect on pellet durability when utilizing the Holmen testing method. When analyzing pellet durability at 30 and 60-second runs in the testing chamber, the 4.4

mm pellets exhibited increased pellet durability ($P \leq 0.05$). There were no interaction effects between corn particle size and pellet diameter on pellet durability, as shown in Table I-5.

Corn particle size did not affect energy consumption at the pellet mill nor change in temperature between conditioned mash feed and hot pellets. Pellet diameter, on the other hand, affected both energy consumption and frictional heat gain as shown in Table I-6. Energy consumption increased when pelleting the 4.4 mm diameter pellets as compared to the 3.5 mm pellets ($P \leq 0.05$). Increased hot pellet temperature also accompanied the increased energy consumption for the larger diameter pellets in comparison to the smaller diameter pellets ($P \leq 0.05$). There were no interaction effects between corn particle size and pellet diameter, as shown in Table I-7.

Live Performance Results

Cumulative BW and period BW data for the main effects of corn particle size and pellet diameter are displayed in Table I-8. There were no differences in BW at any age. There was a difference in period BW gain from 14 to 27 d of age where FC diets produced the most BW gain, CC diets gained the least BW, and WC diets were not different from FC or CC diets ($P \leq 0.05$). After the 14 to 27 d period, there were no subsequent significant differences in BW gain. There were no significant interaction effects between corn particle size and pellet diameter with respect to BW, as shown in Table I-9.

There were neither significant main effects nor interaction effects from corn particle size or pellet diameter on cumulative FI or period FI at any age, as shown in Tables I-10 and I-11, respectively.

Corn particle size affected cumulative FCR at several points and for one period of growth, as shown in Table I-12. At 27 d of age, FC diets exhibited the best FCR while CC diets exhibited the poorest FCR ($P \leq 0.05$) while WC diets were intermediary to FC and CC diets and were not statistically different from either. By 34 d of age, both the FC and WC diets exhibited improved FCR when compared to the CC diets ($P \leq 0.05$). By 41 d of age, there were no significant differences in FCR. From 14-27 d of age the FC diets exhibited improved FCR when compared to the CC and WC diets ($P \leq 0.05$).

Table I-12 also displays the effects of pellet diameter on FCR. By 41 d of age, the 4.4 mm pellets exhibited improved FCR when compared to the 3.5 mm pellets ($P \leq 0.05$). Between 14 and 27 d of age, the 4.4 mm pellets were also able to improve FCR ($P \leq 0.05$). The same trend of improved FCR due to larger pellets followed from 35 to 41 d as well ($P \leq 0.05$), even though there were no differences between the larger and smaller diameter pellets from 28 to 34 d of age. There were no interaction effects (Table I-13) between corn particle size and pellet diameter on FCR.

Corn particle size affected gizzard weight, unlike pellet diameter, as shown in Table I-14. The CC diets produced the largest gizzard weights while the FC diets produced the smallest gizzard weights ($P \leq 0.05$). The WC diets gizzard weights were intermediate between CC and FC gizzard weights. Proventriculus weights were not affected by corn particle size nor pellet diameter. The interaction effect of corn particle size and pellet diameter, presented in Table I-15, produced in no significant differences.

Discussion

Feed Manufacturing

As expected, the CC diets exhibited the largest overall geometric mean diameter while the FC diets exhibited the smallest geometric mean diameter as result of their respective corn particle size inclusions (Table I-3). The WC diets exhibited an intermediate particle size, which suggested that the attempt to mimic the CC diets using WC was unsuccessful. A better understanding of the grinding that occurred as the conditioned mash was forced into the die would give better insight into whether the actual particle sizes of the CC and WC diets were more or less similar after exiting the pellet mill die.

The WC diets exhibited improved pellet durability as compared to the CC diets using the standard tumble box method (Table I-4). As Singh and colleagues (2014) mentioned, analyzing pellet durability in diets that have a vastly different particle size makeup can result in inconsistencies. When analyzing pellet durability as the inclusion of pre-pelleting whole corn increased, a quadratic increase in pellet durability was observed. The WC diets contained more large particles that were not able to pass a #6 or #5 US sieve. These large particles of corn generated from pelleting whole corn were counted as pellets for the PDI equation. The FC and CC diets did not share the ability to retain any of their individual particles composing the diet post-pelleting above a #6 or #5 screen, so they immediately had a disadvantage when compared to the WC diets in pellet durability characteristics.

Utilizing the Holmen testing methods, the 4.4 mm pellets displayed improved pellet durability compared to the 3.5 mm pellets (Table I-4). There was an inherent issue with the Holmen testing method when analyzing pellet durability of different diameter pellets. It was not uncommon to gain durability as the pellet diameter increased. Singh and Ravindran (2014) reported increased pellet durability in ground wheat diets when pellet diameter increased from 3.0 mm to 4.76 mm. When comparing 4.76 mm pellets to 3.0 mm pellets with a 7 mm pellet length, Abdollahi and Ravindran (2013) reported improved pellet durability for the larger diameter pellets. The fixed sieve that acts as the testing chamber in the Holmen NHP100 had no way to account for differences in pellet diameter, unlike the KSU tumble box method that required the use of different size sieves to adjust for pellet diameter differences. Even though the differences were not significant, the numerical trend of improved pellet durability with the larger 4.4 mm diameter pellets continued into the modified testing procedure using the KSU tumble box.

Corn particle size did not affect energy consumption or change in temperature between conditioned mash and hot pellets (Table I-6). On the other hand, the 4.4 pellets required more energy to pellet and experienced an increase in change of temperature between conditioned mash and hot pellets when compared to the 3.5 mm die (Table I-6). This could partially be an effect of the condition of each die. The 3.5 mm die was relatively new and little used, while the 4.4 mm die was continuously used through the near decade the pellet mill operated. The sharper edges of the 3.5 mm die would have been more successful at cutting large particles of coarse and whole corn because of the sharper die face, while the 4.4 mm die would have more of a shearing and grinding effect since its face was more worn. The greater change in temperature between conditioned mash and hot pellets observed when passing the 4.4 mm die was an effect of increased energy input that was passed into the feed in the form of heat.

Live Performance

Corn particle size did not affect cumulative BW at any specific age, but it did affect period BW gain from 14-27 d of age (Table I-8). The FC diets exhibited the best BW gain from 14-27 d of age, while the CC diets exhibited the poorest BW gain. It has not been uncommon for coarse particles to have a deleterious effect on BW and BW gain when first introduced to chicks. Jacobs *et al.* (2010) reported poor BW gain from 0-21 d of age in two separate experiments comparing CC to FC diets. They also observed a linear decrease in metabolizable energy as particle size increased. Jacobs suggested that a corn particle size less than 1000 μm was more suitable for chicks than corn particles over 1000 μm. In agreement, Nir *et al*. (1994) observed poor BW gains for coarse particles from 1-7 d of age in one study and from 7-21 d of age in a separate study.

Poor BW gain for CC also extended into early growing periods. From 18-29 d of age, Dozier *et al*. (2006) reported that broilers fed a diet composed completely of FC out performed broilers fed 35% CC in BW gain. However, from 30-41 d of age, they observed no differences in BW gain. The negative effect of CC did not appear for the cumulative BW at 41 d of age. In some cases, the CC diets were more beneficial for broilers starting at 28 d of age through the finishing period (Xu *et al*., 2015). It was not uncommon for CC to negatively impact BW early, but through the finishing period broilers adjusted to coarse particles to perform just as well, or better, in terms of BW as broilers fed all FC.

Corn particle size affected cumulative FCR at 27 and 34 d of age, as well as from 14-27 d of age (Table I-12). The CC diets exhibited the poorest FCR at 27 d of age, while the FC diets exhibited the best FCR. The WC diets were not different from the FC or CC diets. At 34 d of age, the FC and WC diets exhibited improved FCR compared to the CC diets. By 41 d of age, there were no differences in cumulative FCR. From 14-27 d of age, the FC diets exhibited improved FCR compared to the CC and WC diets. From 35-41 d of age, the WC and CC diets were numerically improved compared the FC diets.

These FCR data were in agreement with other broiler FCR data. From 18-29 d of age, all FC diets exhibited significantly improved FCR over 35% CC diets (Dozier *et al*., 2010). From 30-41 d of age, the negative effect of the CC disappeared and produced numerical improvements compared to FC diets with 15% or 25% inclusion. Bennet *et al*. (2002)

demonstrated the same general trend alluding that an increased particle size was not deleterious to FCR through the finishing period, even though it may have negatively affected FCR early. Xu *et al*. (2015) demonstrated that under some conditions, CC diets eventually improved FCR as compared to diets containing all FC. The increased gizzard function that paralleled increased particle size was thought to allow older birds to better utilize nutrients that young broilers would let pass unabsorbed (Svihus *et al*., 2011). Much like BW, FCR was negatively affected by CC early, but through the finishing period, both BW and FCR were often unaffected or even improved by addition of CC.

Corn particle size affected gizzard size as expected (Table I-14). In concurrence with most data on corn particle size and gizzard weight, the CC diets produced the largest gizzards while the FC diets produced the smallest gizzards. The WC diets exhibited an intermediate gizzard weight. The gross gizzard weights for each of the diets correlated with the particle size of the diets. Gizzard weight generally increased as the size of the particles composing the diets increased (Svihus *et al*., 2004; Amerah *et al*., 2008; Xu *et al*., 2015). The benefit of increased gizzard size included longer residence time of feed inside the gizzard and stimulated gizzard activity with increased CC inclusion that in turn led to more efficient grinding and smaller particle size of digesta (Amerah *et al*., 2008). The smaller particle size of digesta led to increased surface area for enzymatic digestion. Although the current study did not show significant differences in FCR in later periods of growth for the FC, CC, and WC diets, there were differences in the size of gizzards. The different gizzard sizes indicated that the ability to improve FCR for the WC and CC diets was inherently possible through anatomical differences compared to the FC diets, but there was not enough time for these differences to become significant.

The enlarged gizzard size associated with the CC and WC diets indicated that energy was invested in exercising the gizzard. The benefit of CC on FCR was only realized when the benefit of slowed gut passage rate and increased surface area of digesta outweighed the energy invested in muscular activity and growth of the gizzard. The current study suggested that gizzard activity could be beneficial beyond 41 d, but was an expenditure beforehand.

Pellet diameter did not affect FI at any cumulative age or during any period of growth (Table I-10). Abdollahi and Ravindran (2013) demonstrated that smaller 3.0 mm diameter pellets encouraged greater FI from 29-35 d of age when compared to larger 4.76 mm diameter pellets. Fahrenholz (2013) demonstrated that FI decreased when broilers were fed smaller 3.5 mm diameter pellets when compared to 4.4 mm diameter pellets. Cerrate *et al.* (2009) concluded that broiler chicks fed pellets with diameters of 1.59 and 3.17 mm exhibited no difference in FI. There has been no overwhelming acceptance of a general idea of how pellet diameter affected FI, but the current study utilized husbandry practices that would have made witnessing differences in FI difficult to identify. The feeders were shaken twice daily to encourage consumption of feed. Since feed consumption was constantly encouraged, the birds constantly ate. Perhaps a husbandry practice more likely to elicit the effects of pellet diameter on FI would have been to shake feeders only once a day or every other day. In this manner, broilers may have actually shown more of a preference for certain diameter pellets since they were not constantly encouraged to consume feed.

Pellet diameter affected FCR from 14-27 d of age, from 35-41 d of age, and cumulatively at 41 d of age (Table I-12). The larger diameter pellets improved FCR at each of the intervals and cumulatively to 41 d. Through trends in period advantages and a cumulative advantage at the end of the finishing period, its seemed that the larger 4.4 mm pellets were more suitable for FCR when compared to the 3.5 mm pellets. Jensen *et al.* (1962) demonstrated that broiler chicks and poults fed pelleted diets spent considerably less time at the feeder when compared to birds fed mash diets. In the current study, it was possible that the larger diameter pellet allowed broilers to grasp more feed with each attempt, resulting in less time spent at the feeder and more efficient prehension. Efficient feeding became especially important during the finishing phase when FI was at its highest, which explained why the pellet diameter effect on feed conversion was so pronounced during the 35-41 d period.

Conclusions

The WC diets would have saved energy when compared to the FC and CC diets since 10% of their ingredient composition was unprocessed prior to pelleting, and did not result in additional energy consumption at the pellet mill. The WC diets produced a similar response in broiler live performance as the CC diets, suggesting that pre-pelleting inclusion of WC could substitute for CC with respect to broiler live performance.

The FCR improvement resulting from adding coarse particles did not appear in the current study because the benefit of reverse peristalsis and improved digestibly did not outweigh the energy invested in exercise and growth of the gizzard. It appeared that broilers required more than 41 d to benefit from CC when consuming corn of the current particle size and inclusion amount. Larger diameter pellets were more suitable for broilers after 35 d. Larger diameter pellets allowed broilers to grasp more feed in less time which became especially important as feed intake and BW increased while feeder space remained constant.

Table I-1. Composition of broiler starter diets.

Ingredients	Common Starter
	(%)
Fine corn	54.21
SBM (48% CP)	34.76
Poultry fat	2.00
Poultry by-product meal (60% CP)	5.04
Limestone	0.63
Dicalcium phosphate (18.5% P)	1.52
Salt	0.50
DL-Methionine	0.20
L-Lysine	0.06
L-Threonine	0.08
Trace mineral premix[1]	0.20
Vitamin premix[2]	0.05
Choline chloride (60%)	0.20
Selenium[3] (0.06%)	0.05
Saccox 60[4]	0.05
Vermiculite	0.45
Calculated Nutrients	
Protein	24.00
Calcium	1.00
Available phosphorous	0.50
Total lysine	1.32
Total methionine + cysteine	0.95
ME, kcal/g	2.90

[1] Mineral premix provided the following per kg of diet: Mn, 120 mg; Zn, 120 mg; Fe, 80 mg; Cu, 10 mg; I, 2.5 mg; Co, 1 mg.
[2] Vitamin premix provided the following per kg of diet: vitamin A, 6600 IU; vitamin D3, 1.980 IU; vitamin E, 33 IU; vitamin B12, 0.02 mg; biotin, 0.13 mg, menadione, 2 mg; thiamine, 2 mg; riboflavin, 6.6 mg; pantothenic acid, 11 mg; vitamin B6, 4 mg; niacin, 55 mg; folic acid, 1.1 mg.
[3] Selenium premix provided Se at 0.3 mg/kg of feed.
[4] Salinomycin was included at 66 mg/kg of feed (Saccox 60, Huvepharma, Inc., Peachtree City, GA).

Table I-2. Composition of broiler grower diets with three different particle sizes of corn.

Ingredients	Fine Corn (FC)	Coarse Corn (CC)	Whole Corn (WC)
		(%)	
Fine corn	68.13	37.13	58.13
Coarse corn	0.00	31.00	0.00
Whole Corn	0.00	0.00	10.00
SBM (48% CP)		23.35	
Poultry fat		1.00	
Poultry by-product meal (60% CP)		4.05	
Limestone		0.62	
Dicalcium phosphate (18.5% P)		1.46	
Salt		0.50	
DL-Methionine		0.14	
L-Lysine		0.14	
L-Threonine		0.06	
Trace mineral premix[1]		0.20	
Vitamin Premix[2]		0.05	
Choline chloride (60%)		0.20	
Selenium (0.06%)		0.05	
Saccox 60[3]		0.05	
Calculated Nutrients			
Protein		19.00	
Calcium		0.90	
Available phosphorous		0.44	
Total lysine		1.05	
Total methionine + cysteine		0.76	
ME, kcal/g		3.00	

[1] Mineral premix provided the following per kg of diet: Mn, 120 mg; Zn, 120 mg; Fe, 80 mg; Cu, 10 mg; I, 2.5 mg; Co, 1 mg.
[2] Vitamin premix provided the following per kg of diet: vitamin A, 6600 IU; vitamin D3, 1.980 IU; vitamin E, 33 IU; vitamin B12, 0.02 mg; biotin, 0.13 mg, menadione, 2 mg; thiamine, 2 mg; riboflavin, 6.6 mg; pantothenic acid, 11 mg; vitamin B6, 4 mg; niacin, 55 mg; folic acid, 1.1 mg.
[3] Selenium premix provided Se at 0.3 mg/kg of feed.
[4] Salinomycin was included at 66 mg/kg of feed (Saccox 60, Huvepharma, Inc., Peachtree City, GA).

Table I-3. Mean diameter particle size of ground ingredients and diets.

Ingredients	Dgw[1]	Sgw[2]
	(μm)	
Fine corn	328	2.93
Coarse corn	1436	3.23
Fine corn diets	472	2.69
Coarse corn diets	691	3.05
Whole corn diets	576	3.15

[1] Geometric mean diameter was determined by dry sieving according to ASAE method S319.3 with the addition of sieve agitators and 0.5 g of a dispersing agent per 100 g of sample (ASABE, 2007; Stark and Chewning, 2012).
[2] Geometric standard deviation of mean particle size.

Table I-4. Main effect of corn particle size and pellet diameter on pellet durability index (PDI) as determined by tumble box and Holmen methods.

Corn size [1]	Diameter	n [2]	Tumble Box		Holmen	
			Standard [3]	Modified [4]	30 Second [5]	60 Second [6]
	mm		(%)			
Fine		6	85.30[ab]	58.57	84.67	66.83
Coarse		6	83.27[b]	55.27	81.33	65.67
Whole		6	88.07[a]	64.97	85.67	72.83
SEM [7]			1.25	3.46	1.72	4.02
P-value			0.056	0.174	0.216	0.427
	3.5	9	85.58	57.53	80.78[B]	59.78[B]
	4.4	9	85.51	61.67	87.00[A]	77.11[A]
	SEM [7]		1.02	2.82	1.40	3.28
	P-value		0.964	0.322	0.009	0.003

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Corn particle size in each grower diet (Table I-3).
[2] Number of samples collected at the pellet mill die.
[3] Pellet Durability Index (ASAE S269.4) was determined on samples collected at the pellet mill die.
[4] Pellet Durability Index (ASAE S269.4) was determined on samples collected at the pellet mill die with 3 nuts (diameter = 19 mm).
[5] Pellet Durability Index was determined using NHP100 pellet tester set to 30 second interval.
[6] Pellet Durability Index was determined using NHP100 pellet tester set to 60 second interval.
[7] Standard error of mean (SEM) for n=6 samples for each corn size and n=9 samples for each pellet diameter.

Table I-5. Interaction effect of corn particle size and pellet diameter on pellet durability index (PDI) as determined by tumble box and Holmen methods.

			Tumble Box		Holmen	
Corn size[1]	Diameter	n[2]	Standard[3]	Modified[4]	30 Second[5]	60 Second[6]
	mm		(%)			
Fine	3.5	3	86.13	59.27	84.00	60.33
Coarse	3.5	3	82.27	51.33	76.00	55.33
Whole	3.5	3	88.33	62.00	82.33	63.67
Fine	4.4	3	84.47	57.87	85.33	73.33
Coarse	4.4	3	84.27	59.20	86.67	76.00
Whole	4.4	3	87.80	67.93	89.00	82.00
P-value			0.585	0.620	0.198	0.791
SEM[7]			1.77	4.90	2.43	5.68

[1] Corn particle size in each grower diet (Table I-3).
[2] Number of samples collected at the pellet mill die.
[3] Pellet Durability Index (ASAE S269.4) was determined on samples collected at the pellet mill die.
[4] Pellet Durability Index (ASAE S269.4) was determined on samples collected at the pellet mill die with 3 nuts (diameter = 19 mm).
[5] Pellet Durability Index was determined using NHP100 pellet tester set to 30 second interval.
[6] Pellet Durability Index was determined using NHP100 pellet tester set to 60 second interval.
[7] Standard error of mean (SEM) for n=3 samples for each interaction of corn size and pellet diameter.

Table I-6. Main effect of corn particle size and pellet diameter on pellet mill energy utilization and change in temperature between conditioned mash and hot pellets.

Corn size [1]	Diameter	n	Energy utilization	ΔT
	(mm)		(kWh/T)	(°F)
Fine		6	8.58	8.95
Coarse		6	8.46	8.80
Whole		6	8.87	8.90
P-value			0.202	0.985
SEM[2]			0.15	0.61
	3.5	9	8.22[B]	7.84[b]
	4.4	9	9.06[A]	9.92[a]
	P-value		0.001	0.012
	SEM[2]		0.13	0.50

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=6 samples for each corn size and n=9 for each pellet diameter.

Table I-7. Interaction effect of corn particle size and pellet diameter on pellet mill energy utilization and change in temperature between conditioned mash and hot pellets.

Corn size [1]	Diameter	n	Energy utilization	ΔT
	(mm)		(kWh/T)	(°F)
Fine	3.5	3	8.21	7.57
Coarse	3.5	3	8.16	7.70
Whole	3.5	3	8.29	8.27
Fine	4.4	3	8.96	10.33
Coarse	4.4	3	8.76	9.90
Whole	4.4	3	9.44	9.53
P-value			0.448	0.688
SEM[2]			0.22	0.86

[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=3 samples for each interaction of corn size and pellet diameter.

Table I-8. Main effect of corn particle size and pellet diameter on cumulative body weight (BW) and period BW.

			BW					Period BW			
Corn size [1]	Diameter	n	1 d	13 d	27 d	34 d	41 d	1-13 d	14-27 d	28-34 d	35-41 d
	(mm)		(g)								
Fine		12	46	463	1665	2541	3485	417	1202[a]	876	943
Coarse		12	46	468	1633	2490	3422	421	1165[b]	857	932
Whole		12	46	459	1640	2504	3454	412	1181[ab]	864	950
P-value			0.828	0.330	0.170	0.072	0.227	0.337	0.039	0.140	0.643
SEM[2]			0.3	4	13	16	25	4	10	7	14
	3.5	18	46	466	1650	2519	3457	420	1184	869	938
	4.4	18	46	460	1642	2505	3450	413	1182	862	946
	P-value		0.227	0.204	0.600	0.443	0.813	0.191	0.903	0.406	0.643
	SEM[2]		0.2	3	10	13	20	3	8	5	11

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=12 pens of 16 birds for each corn size and n=18 pens of 16 birds for each pellet diameter.

Table I-9. Interaction effect of corn particle size and pellet diameter on cumulative body weight (BW) and period BW.

			BW					Period BW			
Corn size [1]	Diameter	n	1 d	13 d	27 d	34 d	41 d	1-13 d	14-27 d	28-34 d	35-41 d
	(mm)		(g)								
Fine	3.5	6	46	466	1675	2562	3506	419	1209	887	944
Coarse	3.5	6	46	470	1628	2480	3396	424	1158	852	916
Whole	3.5	6	46	463	1646	2514	3470	417	1183	868	955
Fine	4.4	6	46	460	1656	2521	3463	414	1195	865	988
Coarse	4.4	6	46	466	1637	2499	3448	419	1172	862	949
Whole	4.4	6	46	454	1634	2493	3439	408	1179	860	945
	P-value		0.321	0.910	0.708	0.400	0.352	0.910	0.620	0.254	0.486
	SEM[2]		0.2	6	18	22	35	6	14	9	19

[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=6 pens of 16 birds for each interaction of corn size and pellet diameter.

Table I-10. Main effect of corn particle size and pellet diameter on cumulative feed intake (FI) and period FI.

			FI				Period FI			
Corn size [1]	Diameter	n	13 d	27 d	34 d	41 d	1-13 d	14-27 d	28-34 d	35-41 d
	(mm)		(g)							
Fine		12	575	2357	3742	5384	575	1781	1386	1641
Coarse		12	578	2359	3731	5364	578	1780	1371	1632
Whole		12	562	2327	3694	5308	562	1765	1367	1614
P-value			0.205	0.460	0.504	0.517	0.205	0.726	0.556	0.653
SEM [2]			7	20	30	47	7	16	13	21
	3.5	18	574	2361	3748	5380	574	1788	1386	1633
	4.4	18	570	2334	3698	5323	570	1763	1364	1626
	P-value		0.653	0.229	0.163	0.306	0.653	0.185	0.141	0.770
	SEM [2]		6	16	25	39	6	13	10	17

[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=12 pens of 16 birds for each corn size and n=18 pens of 16 birds for each pellet diameter.

Table I-11. Interaction effect of corn particle size and pellet diameter on cumulative feed intake (FI) and period FI.

			FI				Period FI			
Corn size[1]	Diameter	n	13 d	27 d	34 d	41 d	1-13 d	14-27 d	28-34 d	35-41 d
	(mm)		(g)							
Fine	3.5	6	579	2367	3764	5411	579	1788	1396	1648
Coarse	3.5	6	577	2357	3731	5360	577	1780	1375	1629
Whole	3.5	6	566	2361	3748	5370	566	1795	1387	1622
Fine	4.4	6	571	2346	3721	5356	571	1775	1375	1635
Coarse	4.4	6	581	2361	3732	5367	581	1780	1371	1635
Whole	4.4	6	558	2294	3640	5247	558	1736	1346	1607
	P-value		0.764	0.432	0.448	0.630	0.764	0.374	0.592	0.927
	SEM[2]		10	30	43	67	10	22	18	29

[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=6 pens of 16 birds for each interaction of corn size and pellet diameter.

Table I-12. Main effect of corn particle size and pellet diameter on cumulative feed conversion ratio (FCR) and period FCR.

Corn size [1]	Diameter	n	FCR				Period FCR			
			13 d	27 d	34 d	41 d	1-13 d	14-27 d	28-34 d	35-41 d
	(mm)		(g:g)							
Fine		12	1.38	1.46^{B}	1.48^{B}	1.56	1.38	1.49^{B}	1.60	1.79
Coarse		12	1.38	1.49^{A}	1.50^{A}	1.58	1.38	1.53^{A}	1.62	1.77
Whole		12	1.37	1.48^{AB}	1.49^{B}	1.56	1.37	1.51^{A}	1.60	1.77
P-value			0.804	0.003	0.006	0.204	0.837	0.001	0.289	0.683
SEM[2]			0.015	0.005	0.004	0.005	0.015	0.005	0.008	0.017
	3.5	18	1.37	1.48	1.50	1.58^{a}	1.37	1.52^{a}	1.61	1.80^{a}
	4.4	18	1.38	1.47	1.49	1.56^{b}	1.38	1.51^{b}	1.60	1.75^{b}
	P-value		0.371	0.362	0.096	0.012	0.414	0.022	0.153	0.020
	SEM[2]		0.012	0.004	0.004	0.004	0.012	0.003	0.006	0.014

[a, b] Means within each column that possess different superscripts differ significantly ($P \le 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \le 0.01$).
[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=12 pens of 16 birds for each corn size and n=18 pens of 16 birds for each pellet diameter.

Table I-13. Interaction effect of corn particle size and pellet diameter on cumulative feed conversion ratio (FCR) and period FCR.

			FCR				Period FCR			
Corn size[1]	Diameter	n	13 d	27 d	34 d	41 d	1-13 d	14-27 d	28-34 d	35-41 d
	(mm)		(g:g)							
Fine	3.5	6	1.38	1.46	1.48	1.57	1.38	1.49	1.60	1.81
Coarse	3.5	6	1.36	1.49	1.51	1.59	1.36	1.54	1.63	1.80
Whole	3.5	6	1.36	1.48	1.50	1.57	1.36	1.53	1.60	1.79
Fine	4.4	6	1.38	1.46	1.48	1.56	1.38	1.49	1.61	1.77
Coarse	4.4	6	1.39	1.49	1.50	1.56	1.39	1.52	1.58	1.74
Whole	4.4	6	1.37	1.47	1.48	1.55	1.37	1.51	1.59	1.74
	P-value		0.827	0.738	0.587	0.495	0.821	0.355	0.150	0.923
	SEM[2]		0.021	0.007	0.006	0.007	0.021	0.007	0.011	0.025

[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=6 pens of 16 birds for each interaction of corn size and pellet diameter.

Table I-14. Main effect of corn particle size and pellet diameter on gizzard and proventriculus weight.

Corn size [1]	Diameter	n	Gizzard	Proventriculus
	(mm)		(g)	
Fine		24	29.27^{B}	8.86
Coarse		24	34.06^{A}	8.87
Whole		24	32.26^{AB}	9.20
P-value			0.003	0.594
SEM[2]			0.95	0.27
	3.5	36	31.64	8.83
	4.4	36	32.08	9.12
	P-value		0.691	0.338
	SEM[2]		0.78	0.22

$^{A, B}$ Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=24 samples for each corn size and n=36 samples for each pellet diameter.

Table I-15. Interaction effect of corn particle size and pellet diameter on gizzard and proventriculus weight.

Corn size [1]	Diameter	n	Gizzard	Proventriculus
	(mm)		(g)	
Fine	3.5	12	29.67	8.53
Coarse	3.5	12	33.55	8.95
Whole	3.5	12	31.72	9.00
Fine	4.4	12	28.88	9.19
Coarse	4.4	12	34.58	8.78
Whole	4.4	12	32.80	9.40
	P-value		0.730	0.535
	SEM[2]		1.34	0.37

[1] Corn particle size in each grower diet (Table I-3).
[2] Standard error of mean (SEM) for n=12 samples of each interaction of corn size and pellet diameter.

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CHAPTER II

EFFECT OF FAT APPLICATION SITE AND PERCENTAGE FINES ON FEED MANUFACTURING CHARACTERISTICS, BROILER LIVE PERFORMANCE, AND CARCASS PARTS YIELD

Introduction

Mixer added fat (MAF) was proven to be detrimental to pellet quality (Corey *et al.,* 2014; Auttawong, 2015). While fat was an essential formulation parameter required to meet the energy requirements of broilers, it was also noted that poor pellet quality would be detrimental to broiler FCR and BW gain (McKinney & Teeter, 2004). Post-pellet liquid application (PPLA) systems were implemented in feed mills so that liquid fat could be applied to diets after pelleting to maintain pellet quality.

Even after implementing PPLA systems, the generation of some amount of fines at the pellet mill was inevitable. When pelleted feed was directed to the PPLA system, there was a mixture of pellets and fines. Since fines had a greater surface-area-to-mass ratio, there was potential for PPLA fat to preferentially coat fines when compared to pellets. This could result in energy disparities between the two feed forms, which could impact broiler live performance.

Materials and Methods

Feed Manufacturing

The experiment was a 2 x 2 factorial randomized complete block design utilizing two fat application sites (FAS) and two percentages fine. The fat was either added at the mixer or by PPLA. The targeted percentage fines were 0 and 30%. An additional treatment was added to the 2 x 2 structure to examine a modification of the combination of PPLA and 30% fines. All broilers were fed a common starter diet until 908 g was consumed before being transitioned to one of five dietary treatments at approximately 16 d of age.

All feed was manufactured at the North Carolina State University Feed Mill Educational Unit following the guidelines for current Good Manufacturing Practices (cGMP). All corn and soybean meal was ground using a hammer mill (Model 1522, Roskamp Champion, Waterloo, IA) equipped with a 2.4 mm screen on the impact side and a 3.2 mm screen on the release side. The grower and finisher basal diets were batched then blended in a twin shaft counterpoise ribbon mixer (Model TRDB126060, Hayes & Stolz, Fort Worth, TX) for 180 seconds of dry mix time, and then an additional 90 seconds of wet mix time. The basal diets contained 0.5% MAF. The PPLA diets were pelleted as the basal, while the MAF diets were blended with an additional 3.5% MAF for an additional 90 seconds of mix time before pelleting. The diets were conditioned for 30 seconds at 175 °F for the grower diets and 165 °F for the finisher diets in a single pass conditioner (Model C18LL4/F6, California Pellet Mill, Crawfordsville, IN) and then pelleted using a 30 HP California Pellet Mill (Model PM1112-2, California Pellet Mill, Crawfordsville, IN). The pellet mill was equipped with a 4.4 x 28.5 mm die for the common starter diet and a 4.4 x 44 mm die for the grower and finisher diets. Pellets were cooled in a counter flow cooler (Model VK09X09KL, Geelen Counterflow USA, Inc, Orlando, FL). The starter diet was crumbled (Model 624S, Roskamp Champion, Waterloo, IA) while the grower and finisher diets remained in pellet form. The grower and finisher diets were screened (Model 2x4 ROTO-SHAKER, ANDRITZ Inc., Muncy, PA) to ensure 100% pellets were available to generate the 0% fines diets. Any material that passed a US # 6 screen was considered to be fines and was used to generate the 30% fines diets.

All grower and finisher diets were manufactured over a two-day period for each diet phase. The PPLA diets (0.5% MAF) were manufactured on the first day, while the MAF diets (4% MAF) were manufactured on the second day. The basal diets were batched and stored in overhead bins. Equal allotments of each basal batch were used to create the PPLA and MAF runs. After sufficient pellets were collected, the remaining pellets were ground using the crumbler (Model 624S, Roskamp Champion, Waterloo, IA) to generate fines. The MAF-0% fines diets were made by bagging screened pellets directly out of the pellet storage bin.

The rest of the diets required mixing (Model SRM304, Scott Equipment Company, New Prague, MN) beyond pelleting to add required amounts of fat and/or fines. Because the mixer had limited capacity, each blending of materials in the mixer occurred twice. After mixing, each batch was discharged directly into a bagger to minimize the impact of conveyance on pellet quality. Bags from each batch were separated equally on two pallets to ensure that batch-related bag assignment during broiler grow out was randomized. The MAF-30% fines diets were made by combining 70% screened pellets with 30% fines in the mixer where they were subjected to 10 seconds of mixing time. The PPLA-0% fines diets were made by combining 96.5% screened pellets with 3.5% fat subjected to 70 seconds of mixing time. The PPLA-30% fines diets were made by combining 67.5% screened pellets and 29% fines with 3.5% fat that were then subjected to 70 seconds of mixing time.

The additional treatment that modified the 2 x 2 factorial design, and thus created a fifth treatment, utilized a different mixing procedure (Aliquot) to combine the pellets-fines-fat mixture used to create the other PPLA-30% fines diet (Normal). To generate the PPLA-30%-Aliquot diet, pellets and fines were combined with 3.5% fat separately. The fat laden pellets and fat laden fines were then recombined and mixed, thus creating the fifth treatment (Figure II-1).

Incubation

Sixteen trays containing 180 eggs, one tray from each pen of 49-wk-old breeder breeders, were placed in Jamesway 252B incubators. The eggs were preheated for 12 h at 80 °F before being brought to 100.5 °F setpoint with a wet bulb temperature of 83 °F. The exhaust vent was closed at set. As incubation progressed, the exhaust vent was progressively opened. At E3, the set point dry bulb temperature was decreased to 99.5 °F while maintaining a wet bulb temperature of 83 °F. On E12, the dry bulb temperature was decreased and ventilation increased accordingly to maintain an internal egg temperature of 100 °F thereafter.

Grow-out

The rearing of broilers occurred at the North Carolina State University Chicken Educational Unit in House 3, a fully enclosed tunnel-ventilated broiler house with PVC and wire pens on concrete floors covered with wood shavings. A total of forty 1.2 x 1.8 m pens were used, allotting eight replicate pens per dietary treatment. Each pen contained one bell-type drinker and a tube feeder. The litter in each pen was from a previous study that used a common diet for all pens. The litter was left unaltered to reduce broiler intake of shavings.

A total of 320 Ross 708 males and 320 Ross 708 females were allocated to one of five dietary treatments to provide eight males and eight females in each pen. Equal placement of males and females in each pen, or mixed-sex, better-represented current industry practices where broilers were placed straight-run, or unsexed. Upon hatching, each chick was feather sexed and kept separate based on sex, hatching tray, and breeder source pen. To ensure breeder treatment randomization, an equal number of males and females from each breeder treatment were placed in each broiler pen. Chicks were neck tagged before being placed into their assigned pen. Each chick was introduced to water and placed on feed upon entering their pen. Chicks were observed for crop fill within 2 h of placement.

Three supplemental feeding trays and one supplemental drinker were in each pen upon placement. Supplemental feeding trays were removed at 6 d, 10 d, and 12 d. Supplemental drinkers were dumped and refilled daily until their removal at 7 d. All feed was screened for litter before removing the third tray at 12 d, and added back to the tube feeder. Each chick was allotted 908 g of common starter crumble before transitioning to their respective dietary treatments at approximately 16 d of age.

The house was checked twice daily to record maximum and minimum temperatures and to check for any mortality. Thermostats and ventilation were monitored and adjusted daily to achieve protocol objectives for temperature and air quality. Through 12 d, crumbled starter feed was added to supplemental feeders to give chicks access to fresh feed. After 7 d, each tube feeder was shaken daily. After 14 d, each tube feeder was shaken twice daily. Drinkers were dumped to clear litter as needed based on water quality. At 7 d, chicks were counted to confirm mortality records. Feed was adjusted at 14 d for any mortality to ensure all birds had access to the same amount of starter feed prior to transitioning to treatment grower diets. Feed was also adjusted at 35 d for any mortality to ensure each broiler had access to 2.7 kg of grower. The finisher diets were added at 35 d and remained through the rest of the trial.

The lighting schedule was set to 23 h of light to 7 d, 22 h to 14 d, 21 h to 21 d, and then 16 h thereafter. The litter brooding temperatures were set to 97 °F at placement day then decreased to 84 °F in increments by 7 d. The temperature remained constant at 83 °F to 14 d, and 80 °F to 21 d, followed by 75 °F through 44 d. Litter temperatures were measured using an IR gun.

Data Collection

Feed manufacturing data collection included production rates, conditioned mash and hot pellet temperatures, pellet samples for pellet durability analysis, and energy utilization data. One set of data was collected for each sample collection period within the PPLA and MAF runs, with three replicates allocated per treatment, which were separated by 10 min during the middle of the pelleting run. Production rates were taken over a 30 sec interval and used to estimate the production rate in tons/h. Immediately after taking the production rate sample, conditioned mash temperature was recorded via a thermocouple in the conditioner, and another pellet sample was collected in an insulated bucket to be probed with a thermometer to find the maximum pellet temperature for calculations of change in temperature between conditioned mash and hot pellets. A tray sample of pellets was collected and immediately cooled in a custom manufactured experimental cooler for 8 min.

All pellets were subjected to pellet durability testing via the KSU tumble box standard and modified methods as well as the Holmen (Model NHP100, TekPro, United Kingdom) method for 30 and 60 sec. The KSU tumble box was custom manufactured in accordance with ASAE S269.4, and the same standard was followed for testing the durability of each replicate. All pellets were screened with a #5 US sieve in accordance with the standard. 500 g samples of screened pellets, without fines, were subjected to the standard KSU tumble box method with only pellets in the tumbling chamber, as well as the modified KSU method that included three 19mm hex nuts with pellets in the tumbling chamber. After tumbling for 10 min, the pellets were screened and weighed again to represent a proportion of the initial mass added to the tumbling chamber. The Holmen method was performed by adding 100 g of screened pellets to the testing chamber. Pellets were removed directly from the testing chamber and weighed to represent a proportion of the initial mass added to the testing chamber. Tissue paper was placed over the ventilation port to keep fines from exiting the testing chamber and the fines collection chambered was emptied after every other test.

Energy consumption data were collected by the feed mill's automation system (Model 47011, Repete, Sussex, WI) server. Energy utilization, collected as an input continuous variable at the programmable logic controller in horsepower (HP), was recorded automatically every 15 sec. The HP readings were separated by time for each replicate sample collection during the runs. The average HP consumption for each treatment was converted to kW and then coupled with the average production rate for each treatment to calculate energy consumption in kWh/ton.

Six bags from each dietary treatment were probed to provide uniform samples. The feed samples were subjected to sieving with a # 5 US sieve for determination of actual percentage pellets. Gross energy and crude fat analysis was performed for the MAF pellets, PPLA-0% pellets, PPLA-30%-Normal pellets and fines, and PPLA-30%-Aliquot pellets and fines. The gross energy was determined by bomb calorimetry (Model 2901EB, Parr Instrument Company, Moline, IL). The crude fat analysis was performed by Carolina Analytical Services (Bear Creek, NC) using the ether extract method.

Pellet hardness testing was conducted on PPLA and MAF pellets taken directly from the pellet mill as well as pellets from the PPLA-0%, PPLA-30%-Normal, and PPLA-30%-Aliquot diets. The texture analyzer (Model TAXT2, Texture Technologies Corporation, Hamilton, MA) was equipped with a blade 3 mm in width and a 5 kg load cell. Before testing, the texture analyzer was calibrated with a 2 kg test weight. The length of pellets used for analysis were between 5 and 7 mm and positioned so that the blade approached the horizontally positioned pellet perpendicularly. The blade approached and crushed pellets at a speed of 1 mm/s with a force of 0.098 N. The force indicator was set to 0.010 N for the sensitivity of breaking.

Live data collection included male and female group body weight (BW) at placement, 14 d, 28 d, 35 d, and individual BW at 42 d for processing selection for uniformity determination. Feed weighbacks were collected at 14 d, 28 d, 35 d, and 42 d. The BW and feed weighback data were used to calculate feed intake (FI) and adjusted feed conversion ratio (FCR). The FCR was calculated by adding the BW of any mortality from each pen into the FCR calculation. Period BW, FI, and FCR ratios were also calculated.

Processing

During the 42 d BW collection, two broilers of each sex per pen that represented the house average BW were selected for processing at 44 d. Each broiler was weighed and then shackled before stunning, scalding, and picking. After picking, each broiler was removed from its shackle for evisceration. The proventriculus and gizzard of each broiler was removed to be cleaned, blotted dry, and separated before weighing. After evisceration, the broiler was separated into fat pad, leg quarters, wings, breast skin, *Pectoralis* major, Pectoralis minor, and rack.

Data Analysis

The experimental design was a 2 x 2 factorial design with two FAS and two percentage fines. The PPLA-30-Normal and PPLA-30-Aliquot diets were also analyzed together to determine the effect of mixing method. Live performance data were analyzed as a completely randomized block design using the GLM procedure of JMP 11.2 (SAS Institute, Cary, NC) for ANOVA. Means were separated with the LSMeans procedure of JMP and considered statistically significant at $P \leq 0.05$ unless otherwise noted.

Results

Feed Manufacturing

The composition of the broiler starter, grower, and finisher diets are presented in Tables II-1, II-2, and II-3, respectively. FAS significantly affected pellet durability index (PDI) as shown in Table II-4 and Table II-5 for the grower and finisher diets, respectively. For each testing method, the PPLA diets improved PDI as compared to the MAF diets ($P \leq 0.01$). The PPLA diets also improved pellet hardness in a similar manner, as shown in Table II-8. All the pellets tested from PPLA diets were harder than pellets from MAF diets in the grower and finisher diet phase ($P \leq 0.01$).

The FAS significantly affected energy utilization at the pellet mill as well as change in temperature between conditioned mash and hot pellets in the grower and finisher diets, as shown in Table II-7. The PPLA diets required significantly more energy to pellet with respect to the grower and finisher diet phase ($P \leq 0.01$). The PPLA diets also gained significantly more heat through the pellet mill die in the grower ($P \leq 0.05$) and finisher ($P \leq 0.01$) diets.

Table II-6 displays the determined amount of fines found in each diet. All diets allotted to the 0% fines treatments did not differ statistically in the amounts of fines. Likewise, all diets allotted to the 30% fines treatment did not differ statistically in the amounts of fines. Expectedly, when comparing 0 to 30% fines diets, the diets with 0% fines exhibited significantly fewer fines than the diets allotted to 30% fines ($P \leq 0.01$).

Crude fat analysis of portions of the grower and finisher diets are presented in Table II-9. The fines in the PPLA-30%-Normal diet contained significantly more fat than the pellets and fines of any other diet in the grower phase ($P \leq 0.01$). The fines in the PPLA-30%-Normal diet also contained more fat than the pellets that constituted the PPLA-30%-Normal diet in the finisher phase ($P \leq 0.01$). Table II-10 presents the same data separated by feed form and indicated that that the pellets of the PPLA-30%-Normal diet exhibited significantly less fat than any other grower pellets that the broilers consumed while the PPLA-30%-Normal fines exhibited significantly more fat than the PPLA-30%-Aliquot fines among the finisher diets ($P \leq 0.01$).

Gross energy analysis of the grower and finisher diets can be found in Table II-9. For the grower diets, the PPLA-30%-Normal fines possessed significantly more gross energy than their pellet counterparts ($P \leq 0.05$). The same trend was evident in the finisher diets where the PPLA-30%-Normal fines exhibited significantly more gross energy than the pellets from PPLA-30%-Normal diets ($P \leq 0.01$). Table II-10 presents gross energy analysis separated by feed form. In the finisher diets, the PPLA-30%-Normal fines was found to have significantly more gross energy than the PPLA-30%-Aliquot fines ($P \leq 0.01$).

Live Performance

PPLA diets significantly improved male broiler BW compared to MAF diets at 28 d, 35 d, and 42 d as well as increased BW gain for 15-28 d, 29-35 d, and 15-42 d periods ($P \leq 0.01$), as shown in Table II-11. Male broilers consuming diets with 0% fines also exhibited improved BW gain for 29-35 d period when compared to broilers consuming diets with 30% fines ($P \leq 0.05$). There was no significant interaction between FAS and percentage fines on male broiler cumulative BW or period BW gains.

PPLA diets improved female broiler BW over MAF diets at 35 d ($P \leq 0.05$) as shown in Table II-12. An interaction between FAS and percentage fines on female broiler BW was present at 28 d and 35 d as well as during the 15-28 d period. The PPLA-30% produced the greatest BW at 28 and 35 d while the MAF-30% diet produced the smallest BW at 28 and 35 d ($P \leq 0.05$). The PPLA-0% and MAF-0% diets were not significantly different from the aforementioned diets. The exact same trend followed into the 15-28 d female broiler BW gain where the PPLA-30% exhibited the greatest BW gain, MAF-30% exhibited the smallest BW gain, and the PPLA-0% and MAF-0% diets were not significantly different from the previously mentioned diets ($P \leq 0.05$).

Mixed-sex BW data, found in Table 11-13, demonstrates the ability of the PPLA diets to improve cumulative broiler BW at 28 d ($P \leq 0.05$) and 42 d ($P \leq 0.01$) as well as 15-28 d ($P \leq 0.05$), 29-35 d, and 15-42 d ($P \leq 0.01$) period BW gains. There was one interaction between FAS and percentage fines on mixed-sex broiler cumulative BW at 35 d where the PPLA-30% diets exhibited the largest BW and the MAF-30% diets produced the smallest BW ($P \leq 0.05$). While the PPLA-0% and the MAF-0% diets were not statistically different, the broilers consuming the PPLA-0% diet were significantly heavier than broilers consuming the MAF-30% diet and the broilers consuming the MAF-0% diet were significantly smaller than the broilers consuming the PPLA-30% diet ($P \leq 0.05$).

The effect of feed mixing method on male, female, and mixed-sex broiler cumulative BW and period BW gains are presented in Tables II-14, II-15, and II-16, respectively. While feed mixing method did not affect cumulative BW or period BW gains for male and female broilers, it did affect the combined mixed-sex broiler BW gain for 29-35 d. The PPLA-30%-

Normal diet improved BW gain by 25 g during the 29-35 d period compared to the PPLA-30-Aliquot diet ($P \leq 0.05$).

The main and interaction effects of FAS and percentage fines on feed intake (FI) is presented in Table II-17. The FI was significantly reduced when the mixed-sex broilers consumed 30% fines during the 29-35 d ($P \leq 0.01$) and 36-42 d ($P \leq 0.05$) periods. There were no interactions between FAS and percentage fines on either mixed-sex broiler cumulative FI or period FI. Feed mixing method did not affect mixed-sex broiler FI at any cumulative age or during any period, as shown in Table II-18.

The PPLA diets exhibited improved FCR at several ages, as shown in Table II-19. The PPLA diets exhibited improved FCR at 28 d ($P \leq 0.05$) as well as 35 d and 42 d ($P \leq 0.01$). The PPLA diets exhibited improved FCR during the 15-28 d ($P \leq 0.01$) and 15-42 d periods ($P \leq 0.05$). There were no interactions between FAS and percentage fines on broiler FCR. The effect of feed mixing method on broiler FCR, shown in Table II-20, produced a significant difference in period FCR between 29 and 35 d ($P \leq 0.05$). During that period, the PPLA-30%-Normal diet improved FCR compared to the PPLA-30%-Aliquot diet by 7 points.

As a measure of uniformity, the coefficient of variation between dietary treatments separated by sex was calculated and the results are presented in Table II-21. At 42 d, females consuming MAF diets were significantly more uniform than females consuming PPLA diets ($P \leq 0.05$). Male broilers that consumed the PPLA-30%-Normal diet exhibited improved uniformity over the PPLA-30%-Aliquot diet ($P \leq 0.05$) at 42 d.

Processing

The FAS significantly affected breast skin and rack weight in male broilers as shown in Table II-23. The MAF diets increased the weight of the skin covering the breast tissue ($P \leq 0.05$), and decreased the rack weight left after deboning ($P \leq 0.01$). Percentage fines significantly affected *Pectoralis* major weight, also presented in Table II-23, where the male broilers that consumed 30% fines exhibited improved breast tissue yield ($P \leq 0.05$). Table II-24 presents the debone data on a relative basis and shows the same significant effects found when comparing treatments on an absolute weight basis.

Table II-25 presents female carcass parts weights on a gross basis where there were neither significant differences for main effects nor interactions between FAS and percentage fines. Table II-26 presents the relative carcass parts weights, which was significantly affected by FAS and percentage fines. Female broilers consuming PPLA diets exhibited a significantly larger frame after deboning ($P \leq 0.01$). Female broilers consuming 30% fines exhibited significantly smaller leg quarters when compared to female broilers consuming 0% fines ($P \leq 0.05$).

As shown in Table II-27, mixing method affected male broiler gross fat pad weight where male broilers consuming the PPLA-30%-Normal diet exhibited a smaller fat pad compared to male broilers consuming the PPLA-30%-Aliquot diet ($P \leq 0.05$). Likewise, the relative fat pad weight for male broilers was also greater for the male broilers consuming the PPLA-30%-Aliquot diet compared to male broilers consuming the PPLA-30%-Normal diet ($P \leq 0.05$) as shown in Table II-28. Feed mixing method did not affect female broiler gross nor relative carcass parts weights as shown in Tables II-29 and II-30, respectively.

Male relative and gross gizzard weights were improved when the broilers consumed diets with 30% fines compared to the diets with 0% fines ($P \leq 0.05$) as shown in Tables II-31 and II-32. Male broiler proventriculus weight was unaffected by FAS. Neither percentage fines nor FAS produced significant main or interaction effects on female proventriculus and gizzard relative and gross weights as presented in Table II-31. Mixing method did not affect male or female relative and gross proventriculus and gizzard weights as presented in Table II-33 and II-34, respectively.

Discussion

Feed Manufacturing

As would be expected, PPLA diets exhibited improved pellet durability compared to MAF diets (Tables II-4 and II-5). This was in agreement with previous data that demonstrated the negative impact that MAF imposed upon pellet durability (Gehring *et al*., 2011; Corey *et al*., 2014; Loar II *et al*., 2014). While PPLA diets exhibited improved pellet durability, they also required greater energy to produce. A greater inclusion of MAF reduced the energy required to pass conditioned feed through the die. Gehring *et al*. (2011) reported a similar trend where energy consumption decreased as the percentage fat added at the mixer increased. Wamsley and Moritz (2013) negated the negative impact that die thickness imposed on pellet mill energy efficiency by increasing the fat added at the mixer. This occurred because the fat acted as a lubricant between the feed and the die wall, which reduced the friction within the die (Thomas *et al*., 1998).

Since more energy was invested during pelleting the PPLA diets, a greater amount of heat was transferred into the feed as it passed through the die (Table II-7). This was in agreement with Wamsley and Moritz (2013) who suggested that compounds with the inherent ability to reduce energy input at the pellet mill also reduced the amount of heat transferred to the feed between the conditioner and the cooler. As previously mentioned, fat acted as a lubricant. Removing MAF reduced the lubricious value of the feed, resulting in increased hot pellet temperatures.

Similar as was found with pellet durability, the PPLA diets exhibited improved pellet hardness compared to MAF diets even though the elasticity of the pellet did not differ (Table II-8). Gehring *et al*. (2011) explained their improvement in pellet durability due to the removal of MAF as an improvement in pellet hardness, but not elasticity, which agreed perfectly with the data generated in the current study. Van Vliet (1981) also demonstrated that increased MAF reduced pellet hardness. Much like pellet durability, pellet hardness was affected by the amount of fat in the feed because most of the binding between different sugars and proteins in the feedstuffs incorporated water (Thomas *et al*., 1998). If hydrophobic fat molecules were present that discouraged the hydrophilic reaction of binding of particles, the result was poorer pellet durability and hardness.

With respect to the gross energy and crude fat analysis, an important trend was observed from manipulating the mixing method. In each case, PPLA-30%-Normal fines exhibited a greater amount of gross energy or fat when compared to the pellets from the same mixing method (Tables II-9 and II-10). Conversely, when proper amounts of fat were added proportionally to the different parts of the diet, as in the PPLA-30%-Aliquot diets, the fines and pellets did not differ in gross energy or fat. These data definitively demonstrated that fines absorbed more liquid than did pellets when they were sprayed with a liquid in the presence of each other. This occurred because fines had a greater surface-area-to-mass ratio when compared to pellets.

All of the manufactured diets were sieved to determine the percentage pellets compared to fines in the final diets (Table II-6). Ensuring that all of the 30% fines diets were the same and all the 0% fines diets were the same with respect to pellet quality served as verification that the procedures used to mix pellets and fines were adequate and that live performance data could be interpreted without confounding effects.

Live Performance

Male broilers consuming the PPLA diets weighed 120 g more than male broilers consuming MAF diets at 42 d (Table II-11). The positive effect of PPLA diets on male BW was first apparent at 28 d and persisted throughout the study. When Auttawong (2013) removed fat from the mixer, no differences in BW were observed. Loar *et al*. (2014) also did not observe any differences in BW as a result of reducing the amount of MAF. The current study was not in agreement with these previous studies. In the current study, high durability pellets were combined with high percentage fines, which would be unlikely in a real world scenario. Other studies have generally removed MAF to improve pellet quality, while the current study removed MAF to create a durable pellet only to grind them and create poor pellet quality. Durable pellets traditionally accompanied improved pellet quality, but the current study generated a durable pellet with poor pellet quality to determine if PPLA fat would preferentially coat pellets or fines.

Female broiler BW exhibited an interaction between FAS and percentage fines (Table II-12). The females consuming the PPLA-30% diets were significantly heavier than females consuming the MAF-30% diets at 28 and 35 d and approached being significantly heavier at 42 d. It was hypothesized that the reason for the increased BW of females consuming the PPLA-30% diets was primarily the result of altered feeding behavior.

Laying hens have served as a good model for feeding behavior. Quart and Adams (1982) explained that reducing the feeder space or increasing the stocking density reduced the amount of time each individual hen was able to spend feeding. This demonstrated that competition between birds affected their feeding habits. In another trial conducted with laying hens, Cunningham *et al*. (1988) observed reduced egg production among low ranking hens in large population high-density cages. In that particular trial, feeder space per bird was kept constant between low-density and high-density cages. Adding additional laying hens to the cage, while maintaining the same allotted feed space per hen, resulted in decreased egg production by low ranking hens. This demonstrated that the dominant hens took advantage of the increased overall feeder space to induce poorer performance by their low ranking cage mates. It has become understood that dominant birds spend more time at the feeder if the opportunity is presented.

While feeding behavior of broilers was not as well documented as that of laying hens, it can be assumed that larger broilers were more dominant and would spend more time at the feeder and would be the first birds to move to the feeders after new feed was dispensed. Using a mixed-sex pen model, just as in the current study, Nakaue (1981) studied the effect of feeder space on male and female BW. When feeder space was reduced with bird density maintained, male BW did not change, but the females weighed less. The females were apparently subjected to the effect of a reduced feeder space per bird because the males were larger, more dominant, and inevitably spent more time at the feeders.

In the current study, the interaction between FAS and percentage fines for female BW (Table II-12) was probably the result of the aforementioned feeding behaviors. As was expected, the female broilers were smaller than their male pen mates. Therefore, the females gained access to the feeders after the males already completed their meals. The current management practice of shaking feeders twice daily combined with the actual flow of a tube feeder generally appeared to create a feed pan in which pellets were available to the first birds at the feeder while fines were available to the later birds. The females consuming the PPLA-30% diets were heavier than the females consuming the MAF-30% diets probably because the fines that they were consuming contained 2.39% more fat and 184 kcal/kg more gross energy during the growing diet phase and 2.59% more fat and 170 kcal/kg more gross energy during the finishing diet phase.

For mixed-sex BW data, a mix between the male and female growth and feeding characteristics was observed (Table II-13). For the most part, the heavier male BW weighted the data towards following their growth trend for the mixed-sex. Mixed-sex broilers also benefited from PPLA diets at 28 and 42 d as well as during 15-28 d, 29-35 d, and 15-42 d periods, which nearly mirrored the male BW trends. Conversely, an interaction effect was present at 35 d that mimicked the same interaction effect that the females experienced. The broilers consuming the PPLA-30% again weighed more than the broilers that consumed both the MAF-0% diet and the MAF-30% diet. The interaction effect was strong enough in the females to influence the mixed-sex combined BW to overcome the 35 d BW and to apparently overcome differences observed in the males consuming the PPLA diets.

There was no indication that ensuring that the pellets and fines had an equal distribution of fat had any impact on broiler BW performance (Table II-16). The broilers seemed to perform nearly the same regardless of whether or not the fat was partitioned. Perhaps having any amount of fat on the fines helped maintain BW gains because of benefits in texture, palatability, or taste.

Percentage fines affected the broilers as would be expected during 29-35 and 36-42 d periods where broilers presented screened pellets were able to increase their feed consumption (Table II-17). Broilers presented better pellet quality or pellets compared to a mash diet generally exhibited increased feed intake because they can consume more feed with each visit to the feeder pan (Jensen *et al*., 1962; Cutlip *et al*., 2008).

Broilers consuming PPLA diets were observed to more efficiently convert feed to meat from 28 d and persisting through the end of the trial (Table II-19). Cutlip *et al*. (2008) observed a similar pattern when manipulating mash conditioning variables. When pelleting at 200 °F as opposed to 180 °F, an increase in pellet durability was observed. When feeding broilers, offering a harder and more durable pellet has resulted in at least 15 points improvement in FCR (Cutlip *et al*., 2008). The authors hypothesized that the improved FCR was likely the result of improved pellet durability and a decrease in the percentage fines.

Also of interest, McKinney and Teeter (2004) observed that increasing the percentage pellets presented to the broiler at the feed pan resulted in improved FCR. They determined that the physical form of the feed resulted in disparities in energy consumption and utilization. The effective caloric density of the feed increased as pellet quality increased, which meant that fines exhibited a lower effective energy density because the energy input required by the broiler to consume fines was greater. In the current trial, the fines were laden with fat, thus increasing their caloric density. High-energy fines canceled the negative effect associated with consuming the fines. This provided calorically dense fines so that the last bird to the feeder may have better maintained their energy balance, even though they committed more energy to consuming feed.

Another possible reason for the improved FCR when broilers consumed PPLA diets was gut passage rate (Table II-19). Several studies have been conducted that affirmed that an increased dietary fat decreased the transit time of digesta, resulting in more time for enzymatic hydrolysis of nutrients (Mateos and Sell, 1981; Mateos *et al*., 1982). While gastrointestinal transit time was not measured in the current study, the position of the fat surrounding the pellet as opposed to within the pellet could have also played a role in rate of passage. Barekatain *et al*. (2015) reported a decrease in fat digestibility when diets were subjected to heat conditioning as compared to diets that were cold pelleted. Plavnik *et al*. (1997) also reported decreased nutritional quality of energy supplied via liquid fat processed through a pellet mill when compared to liquid fat absorbed to mash diets. The PPLA diets in the current study contained fat that was not subjected to heat, which may have increased the digestibility and nutritional quality of the fat.

Female 42 d BW coefficient of variation (CV) was affected by FAS where the females consuming PPLA diets were less uniform than females consuming MAF diets (Table II-21). This was most likely related to the interaction effect observed for female BW where the females consuming PPLA-30% diets exhibited improved BW over females consuming MAF-30% diets. While it has been clearly demonstrated that less dominant birds will access the feeders after dominant birds, determining exactly when the transition between pellet consumption and fines consumption occurs has proven to be more difficult. Visual observations of the feeder pan 5 min after shaking the feeders revealed a mixture of pellets and fines offered for future feedings until the feeders were again shaken. A potential reason for the decreased uniformity for females consuming PPLA diets was because of the large difference in fat and gross energy between the pellets and fines of the PPLA diets. The most dominant females may have eaten a mixture of pellets and fines during the transition from presentation of pellets to fines only while the least dominant females may have consumed nothing but fines.

Processing

The most critical information obtained through processing the broilers was that male broilers consuming diets with 30% fines exhibited increased *Pectoralis* major yield compared to broilers consuming 0% fines (Tables II-27 and II-28). In a similar manner, the female broilers consuming 30% fines approached significantly improved *Pectoralis* major yield as well (Tables II-29 and II-30). It has been reported that broilers presented poorer quality pellets spend more time at the feeder which may utilize energy that would otherwise go toward muscle accretion (Jensen *et al*., 1962; McKinney and Teeter, 2004; Skinner-Noble *et al*., 2005).

Birds consuming mash feed have been reported to spend three times more time at the feeder than birds consuming pellets (Jensen *et al*., 1962), while resting frequency has been shown to decrease as pellet quality decreased (McKinney and Teeter, 2004). Broilers presented with fines in the feeder pan were more likely to sit and eat at the feeder, creating a more constant supply of feed. A more constant supply of feed over an increased period of feeding may negate the use of glycolytic breast tissue, which was the first tissue utilized when the broiler entered a gluconeogenic state as the result of an absence of feed (Baziz *et al*., 1996). This could be true especially if birds consuming fines were more likely to be eating before the beginning of the scotoperiod, when mobilization of body tissue would be inevitable.

The beneficial effect of enlarged gizzards has been well documented with respect to slowing gut passage rate and improving live performance (Svihus, 2011). Gizzards were harvested in the current study to observe whether the hardness of the PPLA pellets was responsible for any improved FCR of broilers consuming PPLA diets compared to MAF diets. Since no difference in gizzard weight based on FAS was observed (Tables II-31 and II-32), it seemed that a very hard pellet alone was not capable of stimulating the gizzard in a manner similar to particles of coarse grain.

Conclusions

PPLA fat preferentially coated fines when compared to pellets. This occurred because fines, when compared to pellets, had a greater surface-area-to-mass ratio, which allowed them to absorb more liquid fat per unit weight. Fat laden fines proved beneficial for female BW as the increased energy proportioned to the fines was able to ameliorate the negative energy associated with prehension. This allowed the females consuming PPLA diets with a high incidence of fines to exhibit improved BW when compared to females consuming MAF diets with fines since in the latter case there was no additional nutrient to offset the energy investment required to consume the fines, which were likely more available at the time of feeding due to the preferential consumption of pellets by dominant males.

Table II-1. Composition of broiler starter diet.

Ingredients	Starter
	(%)
Fine corn	60.84
SBM (48% CP)	29.35
Poultry fat	1.00
Poultry by-product meal (60% CP)	5.58
Limestone	0.60
Dicalcium phosphate (18.5% P)	1.15
Salt	0.50
DL-Methionine	0.20
L-Lysine	0.14
L-Threonine	0.08
Trace mineral premix[1]	0.20
Vitamin premix[2]	0.05
Choline chloride (60%)	0.20
Selenium[3]	0.05
Coccidiostat[4]	0.05
Calculated Nutrients	
Protein	22.25
Calcium	0.90
Available phosphorous	0.45
Total lysine	1.25
Total methionine + cysteine	0.91
ME, kcal/g	2.94

[1] Mineral premix provided the following per kg of diet: Mn, 120 mg; Zn, 120 mg; Fe, 80 mg; Cu, 10 mg; I, 2.5 mg; Co, 1 mg.
[2] Vitamin premix provided the following per kg of diet: vitamin A, 6600 IU; vitamin D3, 1.980 IU; vitamin E, 33 IU; vitamin B12, 0.02 mg; biotin, 0.13 mg, menadione, 2 mg; thiamine, 2 mg; riboflavin, 6.6 mg; pantothenic acid, 11 mg; vitamin B6, 4 mg; niacin, 55 mg; folic acid, 1.1 mg.
[3] Selenium premix provided Se at 0.3 mg/kg of feed.
[4] Monensin was included at 99 mg/kg of feed (Coban 90, Elanco, Greenfield, IN).

Table II-2. Composition of broiler grower diet.

Ingredients	Grower (%)
Corn	61.95
SBM (48% CP)	28.54
Poultry fat	4.00
Poultry by-product meal (60% CP)	2.00
Limestone	0.64
Dicalcium phosphate (18.5% P)	1.45
Salt	0.50
DL-Methionine	0.19
L-Lysine	0.11
L-Threonine	0.08
Trace mineral premix[1]	0.20
Vitamin premix[2]	0.05
Choline chloride (60%)	0.20
Selenium[3]	0.05
Coccidiostat[4]	0.05
Calculated Nutrients	
Protein	20.00
Calcium	0.80
Available phosphorous	0.40
Total lysine	1.12
Total methionine + cysteine	0.82
ME, kcal/g	3.09

[1] Mineral premix provided the following per kg of diet: Mn, 120 mg; Zn, 120 mg; Fe, 80 mg; Cu, 10 mg; I, 2.5 mg; Co, 1 mg.
[2] Vitamin premix provided the following per kg of diet: vitamin A, 6600 IU; vitamin D3, 1.980 IU; vitamin E, 33 IU; vitamin B12, 0.02 mg; biotin, 0.13 mg, menadione, 2 mg; thiamine, 2 mg; riboflavin, 6.6 mg; pantothenic acid, 11 mg; vitamin B6, 4 mg; niacin, 55 mg; folic acid, 1.1 mg.
[3] Selenium premix provided Se at 0.3 mg/kg of feed.
[4] Monensin was included at 99 mg/kg of feed (Coban 90, Elanco, Greenfield, IN).

Table II-3. Composition of broiler finisher diet.

Ingredients	Finisher
	(%)
Corn	66.91
SBM (48% CP)	24.76
Poultry fat	4.00
Poultry by-product meal (60% CP)	1.00
Limestone	0.60
Dicalcium phosphate (18.5% P)	1.33
Salt	0.50
DL-Methionine	0.15
L-Lysine	0.13
L-Threonine	0.07
Trace mineral premix[1]	0.20
Vitamin Premix[2]	0.05
Choline chloride (60%)	0.20
Selenium[3]	0.05
Coccidiostat[4]	0.05
Calculated Nutrients	
Protein	18.00
Calcium	0.70
Available phosphorous	0.35
Total lysine	1.01
Total methionine + cysteine	0.73
ME, kcal/g	3.15

[1] Mineral premix provided the following per kg of diet: Mn, 120 mg; Zn, 120 mg; Fe, 80 mg; Cu, 10 mg; I, 2.5 mg; Co, 1 mg.

[2] Vitamin premix provided the following per kg of diet: vitamin A, 6600 IU; vitamin D3, 1.980 IU; vitamin E, 33 IU; vitamin B12, 0.02 mg; biotin, 0.13 mg, menadione, 2 mg; thiamine, 2 mg; riboflavin, 6.6 mg; pantothenic acid, 11 mg; vitamin B6, 4 mg; niacin, 55 mg; folic acid, 1.1 mg.

[3] Selenium premix provided Se at 0.3 mg/kg of feed.

[4] Monensin was included at 99 mg/kg of feed (Coban 90, Elanco, Greenfield, IN).

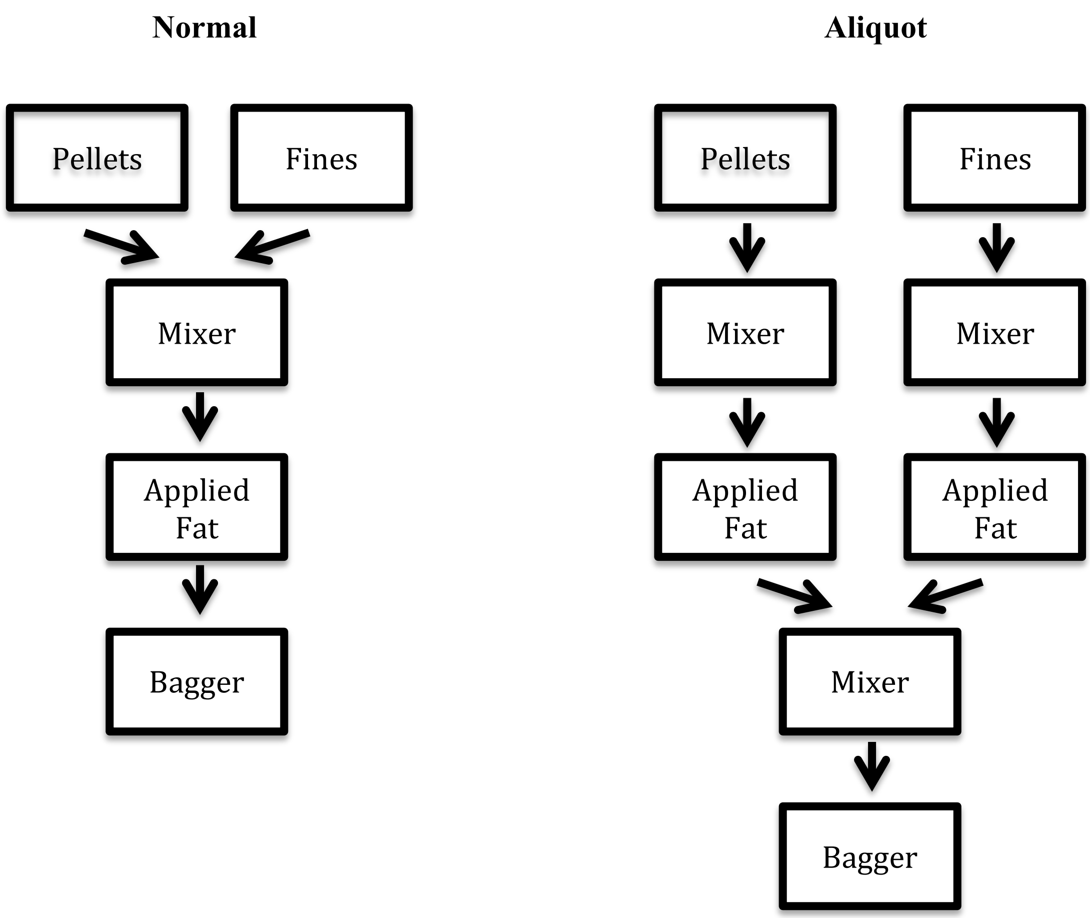

Figure II-1. Diagram of mixing methods used to recombine pellets, fines, and fat for PPLA diets containing 30% fines.

Table II-4. Main effect of fat application site (FAS) on pellet durability index (PDI) as determined by tumble box and Holmen methods in grower diets.

		Tumble Box		Holmen	
FAS [1]	n	Standard[2]	Modified[3]	30 Second[4]	60 Second[5]
		(%)			
Mixer	3	90.47[B]	48.27[B]	90.00[B]	78.67[B]
Post-pellet	3	95.27[A]	81.27[A]	96.00[A]	92.33[A]
P-value		0.002	0.001	0.007	0.001
SEM[6]		0.49	2.32	0.82	1.20

[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site.
[2] Pellet Durability Index (ASAE S269.4) was determined on samples collected at the pellet mill die.
[3] Pellet Durability Index (ASAE S269.4) was determined on samples collected at the pellet mill die with 3 nuts (diameter = 19 mm).
[4] Pellet Durability Index was determined using NHP100 pellet tester set to 30 second interval.
[5] Pellet Durability Index was determined using NHP100 pellet tester set to 60 second interval.
[6] Standard error of mean (SEM) for n=3 samples of each FAS.

Table II-5. Main effect of fat application site (FAS) on pellet durability index (PDI) as determined by tumble box and Holmen methods in finisher diets.

		Tumble Box		Holmen	
FAS [1]	n	Standard[2]	Modified[3]	30 Second[4]	60 Second[5]
		(%)			
Mixer	3	90.73^{B}	55.13^{B}	91.67^{B}	85.33^{B}
PPLA	3	94.53^{A}	78.93^{A}	95.33^{A}	92.33^{A}
P-value		0.001	0.001	0.002	0.002
SEM[6]		0.31	1.17	0.33	0.67

[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site.
[2] Pellet Durability Index (ASAE S269.4) was determined on samples collected at the pellet mill die.
[3] Pellet Durability Index (ASAE S269.4) was determined on samples collected at the pellet mill die with 3 nuts (diameter = 19 mm).
[4] Pellet Durability Index was determined using NHP100 pellet tester set to 30 second interval.
[5] Pellet Durability Index was determined using NHP100 pellet tester set to 60 second interval.
[6] Standard error of mean (SEM) for n=3 samples of each FAS.

Table II-6. Percentage pellets of each diet.

FAS[1]	Fines[2]	Method[3]	n	Grower Pellets	Finisher Pellets
	(%)			(%)	(%)
Mixer	0	Normal	6	95.25^{A}	97.02^{A}
Mixer	30	Normal	6	58.98^{B}	57.36^{B}
PPLA	0	Normal	6	96.37^{A}	97.73^{A}
PPLA	30	Normal	6	64.23^{B}	57.90^{B}
PPLA	30	Aliquot	6	63.58^{B}	61.28^{B}
		P-value		0.001	0.001
		SEM[4]		1.42	1.83

$^{A, B}$ Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1]Fat application site.
[2]Determined by percent of material retained above a US #5 sieve after sifting.
[3]Method of fat application to pellets and fines where normal PPLA diets had fat applied to a mixture of pellets and fines while aliquot PPLA diets had proportioned amounts of fat added to pellets and fines separately before being recombined to make final diet.
[4]Standard error of mean (SEM) for n=6 probed bags of each dietary treatment.

Table II-7. Main effect of fat application site (FAS) on pellet mill energy utilization and change in temperature between conditioned mash and hot pellets in grower and finisher diets.

		Grower		Finisher	
FAS [1]	n	Energy utilization [2]	ΔT [3]	Energy utilization	ΔT
		(kWh/T)	(°F)	(kWh/T)	(°F)
Mixer	3	7.89^{B}	10.5^{b}	8.66^{B}	14.1^{B}
PPLA	3	10.85^{A}	18.3^{a}	12.34^{A}	24.7^{A}
P-value		0.001	0.013	0.001	0.001
SEM [4]		0.27	1.28	0.19	0.55

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site.
[2] Energy data was collected by automation system.
[3] Change in temperature was determined between conditioned mash exiting conditioner and hot pellets leaving the pellet mill die.
[4] Standard error of mean (SEM) for n=3 samples of each FAS.

Table II-8. Effect of fat application site (FAS), percentage fines, and method of recombining pellets and fines on pellet hardness in grower and finisher diets.

				Grower		Finisher	
FAS	Fines	Method[1]	n	Force[2]	Travel[3]	Force	Travel
	(%)			(N)	(mm)	(N)	(mm)
Mixer (4%)	0	Normal	3	11.69^{B}	0.52	12.44^{B}	0.47
Mixer (0.5%)	0	Normal	3	26.44^{A}	0.63	26.40^{A}	0.57
PPLA	0	Normal	3	27.66^{A}	0.56	25.05^{A}	0.57
PPLA	30	Normal	3	30.73^{A}	0.57	24.24^{A}	0.52
PPLA	30	Aliquot	3	33.59^{A}	0.60	25.65^{A}	0.56
		P-value		0.001	0.249	0.001	0.139
		SEM[4]		1.98	0.03	1.18	0.03

[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).

[1] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.

[2] Force required to fracture pellet.

[3] Length of travel required from point of first contact to fracturing of pellet.

[4] Standard error of mean (SEM) for n=3 samples consisting of 15 subsamples of pellets from each dietary treatment.

Table II-9. Effect of fat application site (FAS), percentage fines, mixing method, and feed form on gross energy and crude fat analysis in grower and finisher diets.

					Grower		Finisher	
FAS[1]	Fines	Method[2]	Form	n	Gross Energy[3]	Crude Fat[4]	Gross Energy	Crude Fat
	(%)				(kcal/g)	(%)	(kcal/g)	(%)
Mixer	0	Normal	Pellet	3	3.84^{b}	5.94^{B}	3.85^{BC}	5.42^{BC}
PPLA	0	Normal	Pellet	3	3.92^{ab}	5.81^{B}	3.86^{BC}	5.79^{BC}
PPLA	30	Normal	Pellet	3	3.87^{b}	4.89^{B}	3.75^{C}	4.86^{C}
PPLA	30	Normal	Fines	3	4.03^{a}	8.33^{A}	4.02^{A}	8.01^{A}
PPLA	30	Aliquot	Pellet	3	3.95^{ab}	5.51^{B}	3.88^{ABC}	5.73^{BC}
PPLA	30	Aliquot	Fines	3	3.95^{ab}	6.09^{B}	3.92^{AB}	6.56^{B}
		P-value			0.011	0.001	0.001	0.001
		SEM[5]			0.29	0.31	0.30	0.29

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B, C] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site.
[2] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.
[3] Determined via manual bomb calorimetery.
[4] Determined via ether extract method by Carolina Analytical Services, Bear Creek, NC 27207.
[5] Standard error of mean (SEM) for n=3 samples of portions of each dietary treatment.

Table II-10. Effect fat application site (FAS), percentage fines, and mixing method on crude fat and gross energy analysis in grower and finisher diets separated based on feed form.

				Crude Fat				Gross Energy			
				Grower		Finisher		Grower		Finisher	
FAS [1]	Fines	Method [2]	n	Pellets	Fines	Pellets	Fines	Pellets	Fines	Pellets	Fines
	(%)			(%)				(kcal/g)			
Mixer	0	Normal	3	5.94[A]	-	5.43	-	3.84	-	3.85	-
Mixer	30	Normal	3	-	-	-	-	-	-	-	-
PPLA	0	Normal	3	5.81[A]	-	5.79	-	3.92	-	3.86	-
PPLA	30	Normal	3	4.89[B]	8.33	4.86	8.01[a]	3.87	4.03	3.75	4.02[A]
PPLA	30	Aliquot	3	5.51[A]	6.09	5.73	6.58[b]	3.95	3.95	3.88	3.92[B]
	P-value			0.001	0.084	0.190	0.016	0.143	0.130	0.106	0.003
	SEM			0.08	0.55	0.30	0.26	30	28	36	10

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site.
[2] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.
[3] Determined via ether extract method by Carolina Analytical Services, Bear Creek, NC 27207
[4] Determined via manual bomb calorimetery.
[5] Standard error of mean (SEM) for n=3 samples of portions of each dietary treatment.

Table II-11. Main effect and interaction effect of fat application site (FAS) and percentage fines on cumulative and period body weight (BW) of male broilers.

			BW					Period BW			
FAS [1]	Fines	n	1 d	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)		(g)								
Main Effects											
Mixer		16	43^{b}	463	1657^{B}	2475^{B}	3325^{B}	1195^{B}	818^{B}	850	2862^{B}
PPLA		16	44^{a}	468	1707^{A}	2572^{A}	3445^{A}	1242^{A}	862^{A}	873	2977^{A}
P-value			0.033	0.441	0.007	0.001	0.001	0.002	0.001	0.097	0.001
	0	16	44	458^{b}	1675	2528	3396	1217	854^{a}	867	2938
	30	16	44	473^{a}	1692	2518	3374	1219	824^{b}	873	2901
	P-value		0.242	0.048	0.336	0.645	0.457	0.084	0.031	0.403	0.189
	SEM [2]		0.3	5	13	15	20	9	9	10	19
Interaction Effects											
Mixer	0	8	43	461	1665	2497	3340	1204	833	843	2880
Mixer	30	8	43	465	1648	2453	3309	1185	803	856	2845
PPLA	0	8	44	455	1684	2560	3452	1229	875	892	2996
PPLA	30	8	45	481	1730	2584	3439	1254	849	855	2958
P-value			0.448	0.146	0.081	0.129	0.754	0.118	0.888	0.082	0.954
SEM [2]			0.5	7	18	22	29	13	12	14	27

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Standard error of mean (SEM) for n=16 pens of 16 birds for each FAS and percentage fines, and n=8 for each interaction of FAS and percentage fines.

Table II-12. Main effect and interaction effect of fat application site (FAS) and percentage fines on cumulative and period body weight (BW) of female broilers.

FAS[1]	Fines	n	BW					Period BW			
			1 d	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)		(g)								
Main Effects											
Mixer		16	44	450	1465	2107[b]	2770	1015	642	663	2320
PPLA		16	44	452	1494	2149[a]	2811	1042	655	661	2358
P-value			0.945	0.691	0.114	0.050	0.157	0.052	0.211	0.932	0.144
	0	16	44	446	1465	2123	2799	1020	658	676	2353
	30	16	44	456	1498	2133	2781	1037	640	648	2345
	P-value		0.793	0.139	0.132	0.637	0.532	0.110	0.084	0.074	0.274
	SEM[2]		0.4	5	13	15	20	10	7	11	18
Interaction Effects											
Mixer	0	8	44	450	1471[ab]	2125[ab]	2806	1021[ab]	654	680	2355
Mixer	30	8	44	449	1458[b]	2088[b]	2734	1009[b]	630	645	2284
PPLA	0	8	43	441	1459[ab]	2121[ab]	2793	1018[ab]	662	672	2351
PPLA	30	8	45	464	1529[a]	2178[a]	2829	1065[a]	649	651	2365
P-value			0.127	0.102	0.029	0.031	0.067	0.031	0.602	0.644	0.110
SEM[2]			0.6	7	17	21	28	13	10	15	26

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).

[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).

[2] Standard error of mean (SEM) for n=16 pens of 16 birds for each FAS and percentage fines, and n=8 for each interaction of FAS and percentage fines.

Table II-13. Main effect and interaction effect of fat application site (FAS) and percentage fines on cumulative and period body weight (BW) of mixed-sex broilers.

			BW					Period BW			
FAS [1]	Fines	n	1 d	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)		(g)								
Main Effects											
Mixer		16	44	456	1556^{b}	2293^{B}	3047^{B}	1100^{b}	731^{B}	755	2591^{B}
PPLA		16	44	460	1602^{a}	2359^{A}	3128^{A}	1141^{a}	758^{A}	769	2668^{A}
P-value			0.221	0.490	0.035	0.001	0.001	0.025	0.004	0.209	0.001
	0	16	44	452^{b}	1577	2326	3098	1126	756^{a}	771	2646
	30	16	44	465^{a}	1580	2325	3078	1115	733^{b}	753	2613
	P-value		0.390	0.042	0.896	0.934	0.343	0.569	0.013	0.113	0.099
	SEM [2]		0.3	4	14	11	15	12	6	8	13
Interaction Effects											
Mixer	0	8	44	455	1570	2314^{bc}	3073	1114	745	759	2657
Mixer	30	8	44	457	1542	2271^{c}	3021	1086	717	750	2621
PPLA	0	8	44	448	1585	2338^{ab}	3122	1137	766	783	2607
PPLA	30	8	44	472	1618	2379^{a}	3134	1145	749	755	2633
P-value			0.140	0.069	0.156	0.011	0.136	0.293	0.546	0.366	0.294
SEM [2]			0.4	6	20	15	21	17	11	11	19

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Standard error of mean (SEM) for n=16 pens of 16 birds for each FAS and percentage fines, and n=8 for each interaction of FAS and percentage fines.

Table II-14. Effect of mixing method on cumulative and period body weight (BW) of male broilers.

FAS [1]	Fines	Method [2]	n	BW 1 d	BW 14 d	BW 28 d	BW 35 d	BW 42 d	Period BW 15-28 d	Period BW 29-35 d	Period BW 36-42 d	Period BW 15-42 d
	(%)			(g)								
PPLA	30	Normal	8	45	481	1735	2584	3439	1254	849	855	2958
PPLA	30	Aliquot	8	44	462	1689	2511	3385	1223	822	874	2923
	P-value			0.209	0.089	0.117	0.088	0.243	0.009	0.177	0.371	0.380
	SEM [3]			0.5	7	19	27	43	29	13	14	38

[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.
[3] Standard error of mean (SEM) for n=8 pens of 16 birds for each method of fat application.

Table II-15. Effect of mixing method on cumulative and period body weight (BW) of female broilers.

				BW					Period BW			
FAS[1]	Fines	Method[2]	n	1 d	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)			(g)								
PPLA	30	Normal	8	45	463	1538	2178	2829	1065	649	651	2365
PPLA	30	Aliquot	8	44	452	1501	2127	2781	1048	626	654	2328
	P-value			0.617	0.316	0.373	0.200	0.407	0.456	0.061	0.916	0.463
	SEM[3]			0.6	8	21	26	40	15	8	17	49

[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.
[3] Standard error of mean (SEM) for n=8 pens of 16 birds for each method of fat application.

Table II-16. Effect of mixing method on cumulative and period body weight (BW) of mixed-sex broilers.

				BW					Period BW			
FAS [1]	Fines	Method[2]	n	1 d	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)			(g)								
PPLA	30	Normal	8	45	472	1618	2379	3134	1145	749[a]	755	2662
PPLA	30	Aliquot	8	44	458	1611	2322	3082	1153	724[b]	761	2625
	P-value			0.311	0.146	0.824	0.074	0.168	0.744	0.027	0.665	0.205
	SEM[3]			0.4	7	21	21	24	17	7	14	19

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.
[3] Standard error of mean (SEM) for n=8 pens of 16 birds for each method of fat application.

Table II-17. Main effect and interaction effect of fat application site (FAS) and percentage fines on cumulative and period feed intake (FI) of mixed-sex broilers.

			FI				Period FI			
FAS[1]	Fines	n	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)		(g)							
Main Effects										
Mixer		16	538	2143	3306	4692	1605	1163	1386	4154
PPLA		16	541	2171	3340	4726	1629	1170	1386	4184
P-value			0.669	0.319	0.324	0.463	0.252	0.557	0.968	0.463
	0	16	538	2145	3327	4730	1607	1183^{A}	1403^{a}	4192
	30	16	542	2168	3319	4687	1627	1150^{B}	1369^{b}	4146
	P-value		0.724	0.401	0.797	0.355	0.333	0.009	0.023	0.259
	SEM[2]		7	19	24	32	14	8	10	28
Interaction Effects										
Mixer	0	8	542	2154	3333	4739	1612	1179	1405	4196
Mixer	30	8	533	2131	3278	4645	1598	1147	1367	4112
PPLA	0	8	534	2136	3322	4722	1602	1186	1400	4188
PPLA	30	8	550	2205	3359	4730	1655	1154	1371	4180
P-value			0.200	0.110	0.194	0.280	0.110	0.989	0.758	0.354
SEM[2]			9	27	34	46	20	12	14	40

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Standard error of mean (SEM) for n=16 pens of 16 birds for each FAS and percentage fines, and n=8 for each interaction of FAS and percentage fines.

Table II-18. Effect of mixing method on cumulative and period feed intake (FI) of mixed-sex broilers.

				FI				Period FI			
FAS [1]	Fines	Method [2]	n	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)			(g)							
PPLA	30	Normal	8	550	2205	3359	4730	1655	1154	1371	4180
PPLA	30	Aliquot	8	539	2202	3372	4755	1663	1170	1383	4216
	P-value			0.259	0.946	0.831	0.721	0.826	0.398	0.496	0.574
	SEM [3]			7	31	41	49	24	13	12	63

[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of fat application to pellets and fines; normal PPLA diets had fat applied to a mixture of pellets and fines while aliquot PPLA diets had proportioned amounts of fat added to pellets and fines separately before being recombined to make final diet.
[2] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.
[3] Standard error of mean (SEM) for n=8 pens of 16 birds for each method of fat application.

Table II-19. Main effect and interaction effect of fat application site (FAS) and percentage fines on cumulative and period feed conversion ratio (FCR) on mixed-sex broilers.

			FCR				Period FCR			
FAS [1]	Fines	n	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)		(g:g)							
Main Effects										
Mixer		16	1.30	1.41^{a}	1.47^{A}	1.57^{a}	1.46^{A}	1.60	1.85	1.61^{a}
PPLA		16	1.30	1.40^{b}	1.45^{B}	1.54^{b}	1.43^{B}	1.56	1.83	1.58^{b}
P-value			0.961	0.027	0.009	0.024	0.007	0.073	0.431	0.012
	0	16	1.32^{a}	1.40	1.46	1.55	1.44	1.57	1.84	1.59
	30	16	1.29^{b}	1.41	1.46	1.55	1.45	1.59	1.84	1.60
	P-value		0.020	0.937	0.684	0.885	0.091	0.481	0.640	0.530
	SEM [2]		0.012	0.005	0.006	0.007	0.006	0.014	0.015	0.007
Interaction Effects										
Mixer	0	8	1.32	1.41	1.47	1.57	1.45	1.59	1.87	1.61
Mixer	30	8	1.29	1.41	1.48	1.56	1.47	1.61	1.83	1.61
PPLA	0	8	1.32	1.40	1.45	1.54	1.43	1.56	1.82	1.58
PPLA	30	8	1.29	1.40	1.45	1.54	1.44	1.56	1.84	1.58
P-value			0.876	0.757	0.588	0.868	0.608	0.769	0.190	0.876
SEM [2]			0.018	0.007	0.008	0.009	0.009	0.020	0.021	0.010

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Standard error of mean (SEM) for n=16 pens of 16 birds for each FAS and percentage fines, and n=8 for each interaction of FAS and percentage fines.

Table II-20. Effect of mixing method on cumulative and period feed conversion ratio (FCR) on mixed-sex broilers.

				FCR				Period FCR			
FAS [1]	Fines	Method [2]	n	14 d	28 d	35 d	42 d	15-28 d	29-35 d	36-42 d	15-42 d
	(%)			(g:g)							
PPLA	30	Normal	8	1.29	1.40	1.45	1.54	1.44	1.56[b]	1.84	1.59
PPLA	30	Aliquot	8	1.30	1.42	1.48	1.57	1.46	1.63[a]	1.83	1.61
	P-value			0.481	0.251	0.070	0.159	0.303	0.048	0.826	0.195
	SEM [3]			0.015	0.012	0.012	0.13	0.014	0.020	0.22	0.014

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.
[3] Standard error of mean (SEM) for n=8 pens of 16 birds for each method of fat application.

Table II-21. Main effect and interaction effect of fat application site (FAS) and percentage fines on body weight (BW) coefficient of variation separated by sex at 42 d.

FAS [1]	Fines (%)	n	Male	Female
			(BW % CV)	
Main Effects				
Mixer		16	7.97	6.22[b]
PPLA		16	6.91	8.02[a]
P-value			0.211	0.022
	0	16	7.25	6.94
	30	16	7.63	7.30
	P-value		0.648	0.627
	SEM[2]		0.587	0.518
Interaction Effects				
Mixer	0	8	7.74	5.66
Mixer	30	8	8.20	6.79
PPLA	0	8	6.75	8.23
PPLA	30	8	7.06	7.81
P-value			0.931	0.299
SEM[2]			0.831	0.733

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).

[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).

[2] Standard error of mean (SEM) for n=16 pens of 16 birds for each FAS and percentage fines and n=8 for each interaction of FAS and percentage fines.

Table II-22. Effect of mixing method on body weight (BW) coefficient of variation separated by sex at 42 d.

FAS [1]	Fines (%)	Method [2]	n	Male	Female
				(BW % CV)	
Main Effects					
PPLA	30	Normal	8	7.06[b]	7.81
PPLA	30	Aliquot	8	9.19[a]	8.83
	P-value			0.047	0.348
	SEM [3]			0.694	0.738

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of recombination of fat, pellets, and fines. Post pellet liquid application (PPLA) diets were pelleted with 0.5% fat with the remaining 3.5% fat added after pelleting. Normal PPLA diets were generated by adding 3.5% of PPLA fat onto pellets or a combination of pellets and fines. Aliquot PPLA diets were generated by adding 30% of the PPLA fat solely onto the fines and 70% of the PPLA fat solely onto the pellets. The fat laden feed forms were then recombined to generate a complete diet.
[3] Standard error of mean (SEM) for n=8 pens of 16 birds for each method of fat application.

Table II-23. Main effect and interaction effect of fat application (FAS) site and percentage fines on carcass parts weight of male broilers at 44 d.

FAS[1]	Fines	n	Carcass Parts Weights								
			Live BW	Carcass Weight	Fat	Legs and Thighs	Wing	Skin	*Pectoralis* Major	*Pectoralis* Minor	Rack
	(%)		(g)								
Main Effects											
MAF		32	3588	2857	49	807	261	109[a]	814	157	633[B]
PPLA		32	3538	2851	47	800	259	95[b]	804	154	672[A]
P-value			0.055	0.792	0.467	0.478	0.552	0.014	0.530	0.482	0.001
	0	32	3553	2850	49	809	258	101	793[b]	155	661
	30	32	3574	2859	46	799	262	103	825[a]	155	645
	P-value		0.416	0.670	0.281	0.337	0.314	0.722	0.031	0.928	0.178
	SEM[2]		18	15	2	7	2	4	11	3	8
Interaction Effects											
MAF	0	16	3551[ab]	2832	49	807	259	109	793	156	634
MAF	30	16	3625[a]	2882	49	808	264	109	835	158	633
PPLA	0	16	3555[ab]	2867	50	810	258	94	793	155	688
PPLA	30	16	3522[b]	2835	43	790	260	98	816	153	657
P-value			0.041	0.057	0.217	0.323	0.671	0.680	0.527	0.611	0.200
SEM[2]			26	21	3	10	3	5	15	4	11

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Standard error of mean (SEM) for n=32 males for each FAS and percentage fines and n=16 males for each interaction of FAS and percentage fines.

Table II-24. Main effect and interaction effect of fat application site (FAS) and percentage fines on percentage carcass parts weight of male broilers at 44 d.

FAS[1]	Fines	n	Percentage Carcass Parts Weight						
			Fat	Legs and Thighs	Wing	Skin	*Pectoralis* Major	*Pectoralis* Minor	Rack
	(%)		(g/100 g carcass)						
Main Effects									
MAF		32	1.71	28.27	9.14	3.82[a]	28.46	5.49	22.17[B]
PPLA		32	1.63	28.06	9.09	3.35[b]	28.21	5.39	23.58[A]
P-value			0.446	0.530	0.634	0.015	0.591	0.482	0.001
	0	32	1.74	28.40	9.07	3.57	27.80[b]	5.44	23.17
	30	32	1.61	27.94	9.16	3.16	28.88[a]	5.44	22.58
	P-value		0.253	0.168	0.466	0.823	0.023	0.978	0.089
	SEM[2]		0.077	0.232	0.081	0.135	0.325	0.010	0.241
Interaction Effects									
MAF	0	16	1.72	28.53	9.14	3.87	27.96	5.50	22.36
MAF	30	16	1.70	28.01	9.14	3.78	28.97	5.49	21.98
PPLA	0	16	1.75	28.26	9.00	3.26	27.65	5.39	23.97
PPLA	30	16	1.51	27.87	9.17	3.44	28.78	5.39	23.18
P-value			0.329	0.850	0.450	0.481	0.892	0.972	0.552
SEM[2]			0.109	0.328	0.114	0.191	0.460	0.139	0.341

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Standard error of mean (SEM) for n=32 males for each FAS and percentage fines and n=16 males for each interaction of FAS and percentage fines.

Table II-25. Main effect and interaction effect of fat application site (FAS) and percentage fines on carcass parts weight of female broilers at 44 d.

			Carcass Parts Weights								
FAS[1]	Fines	n	Live BW	Carcass Weight	Fat	Legs and Thighs	Wing	Skin	*Pectoralis* Major	*Pectoralis* Minor	Rack
	(%)						(g)				
Main Effects											
MAF		32	2818	2239	37	591	23	81	661	143	514
PPLA		32	2810	2236	33	596	207	89	649	130	515
P-value			0.719	0.892	0.291	0.471	0.182	0.222	0.417	0.133	0.835
	0	32	2806	2227	35	598	203	83	643	136	515
	30	32	3822	2248	35	288	206	86	667	137	514
	P-value		0.411	0.249	0.964	0.172	0.343	0.652	0.082	0.855	0.994
	SEM[2]		14	13	3	5	2	5	10	6	6
Interaction Effects											
MAF	0	16	2814	2239	36	597	202	82	651	147	512
MAF	30	16	2822	2239	38	584	204	79	671	139	515
PPLA	0	16	2797	2215	35	599	205	84	635	125	517
PPLA	30	16	2823	2258	32	593	208	94	664	136	514
P-value			0.660	0.246	0.478	0.591	0.885	0.355	0.727	0.234	0.715
SEM[2]			15	19	4	7	3	7	14	8	9

[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).

[2] Standard error of mean (SEM) for n=32 females for each FAS and percentage fines, and n=16 females for each interaction of FAS and percentage fines.

Table II-26. Main effect and interaction effect of fat application site (FAS) and percentage fines on percentage carcass parts weight of female broilers at 44 d.

			Percentage Carcass Parts Weight						
FAS[1]	Fines	n	Fat	Legs and Thighs	Wing	Skin	*Pectoralis* Major	*Pectoralis* Minor	Rack
	(%)		(g/100 g carcass)						
Main Effects									
MAF		32	1.66	26.38	9.06	3.61	29.51	6.37	22.17[B]
PPLA		32	1.49	26.65	9.25	3.98	29.01	5.83	23.58[A]
P-value			0.329	0.341	0.145	0.213	0.338	0.135	0.000
	0	32	1.59	26.85[a]	9.14	3.75	28.85	6.09	23.17
	30	32	1.56	26.18[b]	9.17	3.84	29.67	6.11	22.58
	P-value		0.855	0.012	0.803	0.757	0.055	0.970	0.089
	SEM[2]		0.118	0.200	0.093	0.212	0.366	0.256	0.241
Interaction Effects									
MAF	0	16	1.60	26.68	9.00	3.68	29.06	6.56	22.94
MAF	30	16	1.71	26.08	9.11	3.53	29.95	6.19	23.05
PPLA	0	16	1.58	27.03	9.27	3.82	28.63	5.63	23.11
PPLA	30	16	1.41	26.28	9.23	4.15	29.39	6.03	22.88
P-value			0.422	0.787	0.563	0.424	0.893	0.285	0.253
SEM[2]			0.169	0.288	0.133	0.304	0.526	0.368	0.320

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[A, B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Standard error of mean (SEM) for n=32 females for each FAS and percentage fines, and n=16 females for each interaction of FAS and percentage fines.

Table II-27. Effect of mixing method on carcass parts weight of male broilers at 44 d.

				Carcass Parts Weights								
FAS[1]	Fines	Method[2]	n	Live BW	Carcass Weight	Fat	Legs and Thighs	Wing	Skin	*Pectoralis* Major	*Pectoralis* Minor	Rack
	(%)			(g)								
Main Effects												
PPLA	30	Normal	16	3522	2835	43^{b}	790	260	95	816	153	657
PPLA	30	Aliquot	16	3561	2850	53^{s}	790	258	98	821	156	662
	P-value			0.349	0.684	0.033	0.981	0.712	0.832	0.824	0.629	0.770
	SEM[3]			29	26	3	12	4	7	17	4	12

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of fat application to pellets and fines; normal PPLA diets had fat applied to a mixture of pellets and fines while aliquot PPLA diets had proportioned amounts of fat added to pellets and fines separately before being recombined to make final diet.
[3] Standard error of mean (SEM) for n=16 males for each mixing method of PPLA-30% diets.

Table II-28. Effect of mixing method on percentage carcass parts weight of male broilers at 44 d.

				Percentage Carcass Parts Weights						
FAS[1]	Fines	Method[2]	n	Fat	Legs and Thighs	Wing	Skin	*Pectoralis* Major	*Pectoralis* Minor	Rack
	(%)			(g/100 g carcass)						
Main Effects										
PPLA	30	Normal	16	1.51[b]	27.73	9.17	3.44	28.78	5.39	23.18
PPLA	30	Aliquot	16	1.85[s]	27.87	9.06	3.35	28.81	5.47	23.24
	P-value			0.033	0.766	0.460	0.784	0.974	0.693	0.904
	SEM[3]			0.106	0.334	0.109	0.233	0.520	0.136	0.375

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).
[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of fat application to pellets and fines; normal PPLA diets had fat applied to a mixture of pellets and fines while aliquot PPLA diets had proportioned amounts of fat added to pellets and fines separately before being recombined to make final diet.
[3] Standard error of mean (SEM) for n=16 males for each mixing method of PPLA-30% diets.

Table II-29. Effect of mixing method on carcass parts weight of female broilers at 44 d.

FAS[1]	Fines	Method[2]	n	Carcass Parts Weights								
				Live BW	Carcass Weight	Fat	Legs and Thighs	Wing	Skin	*Pectoralis* Major	*Pectoralis* Minor	Rack
	(%)			(g)								
Main Effects												
PPLA	30	Normal	16	2827	2259	31	594	208	96	665	136	510
PPLA	30	Aliquot	16	2848	2259	30	599	207	81	669	138	517
	P-value			0.555	0.995	0.832	0.689	0.676	0.224	0.840	0.593	0.660
	SEM[3]			26	24	3	9	3	9	15	3	12

[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of fat application to pellets and fines; normal PPLA diets had fat applied to a mixture of pellets and fines while aliquot PPLA diets had proportioned amounts of fat added to pellets and fines separately before being recombined to make final diet.
[3] Standard error of mean (SEM) for n=16 females for each mixing method of PPLA-30% diets.

Table II-30. Effect of mixing method on percentage carcass parts weight of female broilers at 44 d.

FAS[1]	Fines	Method[2]	n	Percentage Carcass Parts Weights: Fat	Legs and Thighs	Wing	Skin	*Pectoralis* Major	*Pectoralis* Minor	Rack
	(%)			(g/100 g carcass)						
Main Effects										
MAF	30	Normal	16	1.38	26.32	9.24	4.25	29.41	6.03	22.57
PPLA	30	Aliquot	16	1.34	26.51	9.16	3.62	29.62	6.12	22.86
	P-value			0.838	0.708	0.460	0.251	0.769	0.611	0.565
	SEM[3]			0.142	0.347	0.109	0.388	0.506	0.127	0.360

[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of fat application to pellets and fines; normal PPLA diets had fat applied to a mixture of pellets and fines while aliquot PPLA diets had proportioned amounts of fat added to pellets and fines separately before being recombined to make final diet.
[3] Standard error of mean (SEM) for n=16 females for each mixing method of PPLA-30% diets.

Table II-31. Main effect and interaction effect of fat application (FAS) site and percentage fines on relative gizzard and proventriculus weights of male and female broilers at 44 d.

			Male		Female	
FAS [1]	Fines	n	Proventriculus	Gizzard	Proventriculus	Gizzard
	(%)		(g/100 g BW)			
Main Effects						
Mixer		32	0.19	1.07	0.21	1.14
PPLA		32	0.19	1.08	0.18	1.08
P-value			0.246	0.944	0.125	0.230
	0	32	0.19	1.01[b]	0.19	1.07
	30	32	0.19	1.14[a]	0.20	1.15
	P-value		0.582	0.028	0.645	0.160
	SEM[2]		0.004	0.042	0.009	0.041
Interaction Effects						
Mixer	0	16	0.19	0.96	0.20	1.05
Mixer	30	16	0.18	1.18	0.21	1.23
PPLA	0	16	0.19	1.06	0.18	1.09
PPLA	30	16	0.20	1.09	0.18	1.06
P-value			0.298	0.105	0.965	0.068
SEM[2]			0.006	0.061	0.014	0.058

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).

[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).

[2] Standard error of mean (SEM) for n=32 males and females for each FAS and percentage fines, and n=16 males and females for each interaction of FAS and percentage fines.

Table II-32. Main effect and interaction effect of fat application site (FAS) and percentage fines on gizzard and proventriculus weights of male and female broilers at 44 d.

FAS[1]	Fines (%)	n	Male Proventriculus (g)	Male Gizzard (g)	Female Proventriculus (g)	Female Gizzard (g)
Main Effects						
Mixer		32	6.73	38.45	5.68	32.09
PPLA		32	6.89	38.27	5.74	30.61
P-value			0.389	0.928	0.757	0.338
	0	32	6.83	35.91[b]	5.65	30.15
	30	32	6.80	40.81[a]	5.79	32.55
	P-value		0.872	0.019	0.423	0.124
	SEM[2]		0.131	1.541	0.134	1.17
Interaction Effects						
Mixer	0	16	6.81	34.09	5.59	29.62
Mixer	30	16	6.67	42.83	5.79	34.57
PPLA	0	16	6.85	37.74	5.70	30.68
PPLA	30	16	6.93	38.80	5.78	30.53
P-value			0.508	0.064	0.738	0.102
SEM[2]			0.188	2.21	0.196	1.712

[a, b] Means within each column that possess different superscripts differ significantly ($P \leq 0.05$).

[1] Fat application site included 4% mixer added fat (Mixer) or 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).

[2] Standard error of mean (SEM) for n=32 males and females for each FAS and percentage fines, and n=16 males and females for each interaction of FAS and percentage fines.

Table II-33. Effect of mixing method on relative gizzard and proventriculus weights of male and female broilers at 44 d.

FAS [1]	Fines	Method[2]	n	Male Proventriculus	Male Gizzard	Female Proventriculus	Female Gizzard
	(%)			(g/100 g BW)			
Main Effects							
PPLA	30	Normal	16	0.20	1.09	0.18	1.00
PPLA	30	Aliquot	16	0.19	1.09	0.19	1.12
P-value				0.417	0.968	0.682	0.185
SEM[3]				0.005	0.065	0.016	0.060

[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of fat application to pellets and fines; normal PPLA diets had fat applied to a mixture of pellets and fines while aliquot PPLA diets had proportioned amounts of fat added to pellets and fines separately before being recombined to make final diet.
[3] Standard error of mean (SEM) for n=16 males and females for each mixing method of PPLA-30% diets.

Table II-34. Effect of mixing method on gizzard and proventriculus weights of male and female broilers at 44 d.

FAS [1]	Fines (%)	Method[2]	n	Male Proventriculus (g)	Male Gizzard (g)	Female Proventriculus (g)	Female Gizzard (g)
Main Effects							
PPLA	30	Normal	16	6.98	38.40	5.81	28.03
PPLA	30	Aliquot	16	6.88	39.22	5.76	32.87
P-value				0.692	0.804	0.836	0.057
SEM[3]				0.185	2.336	0.188	1.755

[1] Fat application site included 0.5% mixer added fat with the additional 3.5% fat added post pellet (PPLA).
[2] Method of fat application to pellets and fines; normal PPLA diets had fat applied to a mixture of pellets and fines while aliquot PPLA diets had proportioned amounts of fat added to pellets and fines separately before being recombined to make final diet.
[3] Standard error of mean (SEM) for n=16 males and females for each mixing method of PPLA-30% diets.

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CHAPTER III

EFFECT OF A LIGNOSULFONATE PELLET BINDER ON PELLET DURABILITY IN MARGINAL PELLETING CONDITIONS

Introduction

McKinney & Teeter (2004) demonstrated that pellet quality must be maintained to efficiently rear broilers. While Behnke (2001) described several factors that could affect pellet quality, the most influential factors were feed formulation, mash conditioning parameters, and mash diet particle size. In instances where these factors negatively impacted pellet quality, one method to address diminishing pellet durability was through addition of a lignosulfonate pellet binder (Winowiski, 2015). The addition of lignosulfonate could potentially alleviate poor pellet quality in marginal pelleting conditions pertaining to feed formulation, mash conditioning temperature, and mash particle size.

Materials and Methods

Trial 1

The experiment was conducted by pelleting batches of a broiler starter diet with and without a lignosulfonate pellet binder over a range of five conditioning temperatures between 164 and 180 °F. The basal control feed was batched using a twin shaft counterpoise ribbon mixer (Model TRDB126060, Hayes & Stolz, Fort Worth, TX) for 180 sec of dry mixing time, followed by an additional 90 sec of wet mixing time. After batching the basal control, the feed was separated into individual 4 kg batches prior to pelleting. Half of the batches remained as the basal control, while the other half of the batches received an addition of lignosulfonate (LS) at 0.5% on top of the basal formulation. All of the individual batches were thoroughly mixed in a clean bucket by hand before being subjected to pelleting.

A laboratory scale pellet mill (Model CL-2, California Pellet Mill, Crawfordsville, IN) was employed for pelleting. The pellet mill was warmed to 164 °F before pelleting treatment batches. Each batch required approximately 150 sec to pellet. The batches were pelleted continuously, allowing the feed hopper to clear only momentarily before adding the next batch. To ensure flushing of lignosulfonate between treatments, the first 60 sec of pellets produced were discarded. The next 60 sec of pellets produced were collected for durability testing, while the last 30 sec of pellets produced were also discarded. After a combination of control and LS treatments were pelleted at each temperature, the steam valve on the conditioner was opened to allow the conditioning temperature to rise. The order in which control and LS treatments were pelleted at each temperature was randomized to reduce the impact that continuously warming pelleting equipment might have on pellet durability.

The conditioned mash temperature was determined using a thermometer. All pellet durability testing was conducted using the Holmen method (Model NHP100, TekPro, United Kingdom) for 30 sec. The Holmen method was performed by adding 100 g of screened pellets to the testing chamber. Pellets were removed directly from testing chamber and weighed after being subjected to testing to represent a proportion of the initial mass added to the testing chamber.

All data were analyzed using the GLM procedure of JMP 11.2 (SAS Institute, Cary, NC). Simple linear regression was employed with the temperature variable set as a continuous factor and the lignosulfonate variable set as a nominal factor. Means were separated with the LSMeans procedure of JMP and considered statistically significant at $P \leq 0.05$ unless otherwise noted.

Trial 2

The experiment was a 2 x 2 x 2 factorial design utilizing two percentages of mixer added fat (1.5 and 3%), two percentages of coarse corn (0 and 13.5%) as a portion of the entire diet, and two percentages of a lignosulfonate pellet binder (0% and 0.5%). The base formulation was a broiler finisher ration. All fine corn was ground through a hammer mill (Model 1522, Roskamp Champion, Waterloo, IA) equipped with a pair of 2.4 mm screens. All coarse corn was ground through a double pair roller mill (Model C128889, RMS, Sea, SD) with a top gap setting of 30% open and a bottom gap setting of 20% open. The geometric mean diameter of the fine corn was 326 μm while the coarse corn was 909 μm. Fine corn was used to replace fat for the 1.5% fat diets.

The basal control feed was mixed in a double-ribbon mixer (Model SRM304, Scott Equipment, New Prague, MN) with 1.5% fat, no coarse corn, and no lignosulfonate for 180 sec of dry mixing time, followed by an additional 90 sec of wet mixing time. After batching the basal control, the feed was separated into individual 3.4 kg batches to prior to pelleting. The 3.4 kg batches were brought to 4 kg through the addition of corn, fat, lignosulfonate, or a combination of the ingredients as appropriate. The lignosulfonate was added on top of the basal formulation, while the corn and fat were added as parts of the basal formulation. After adding the appropriate ingredients, the individual batches were thoroughly mixed by hand in a clean bucket. Three replicate batches were created for each combination of factors creating twelve replicates for each level of fat, coarse corn, and lignosulfonate.

The pellet collection process was the same as described in *Trial 1*. The pelleting was separated into three blocks and the order within each block was randomized to account for the impact of continuously warming pelleting equipment on pellet durability.

Pellet mill amperage and conditioned mash temperatures were recorded for each treatment batch using a data logger (Model U12-013, Onset, Cape Cod, MA). All pellet durability testing was conducted in the same manner as described in *Trial 1.*

Pellet durability, pellet mill amperage, and conditioned mash temperature were analyzed as a completely randomized block design using the GLM procedure of JMP 11.2 (SAS Institute, Cary, NC) for ANOVA. Means were separated with the LSMeans procedure of JMP and considered statistically significant at $P \leq 0.05$ unless otherwise noted.

Trial 3

The experiment was conducted by pelleting batches of a balanced protein broiler diet with and without a lignosulfonate pellet binder over a range of nine levels of crude protein ranging from 16 to 24%. Two 16 and 24% protein basal diets were mixed in a double-ribbon mixer (Model SRM304, Scott Equipment, New Prague, MN) for 180 sec of dry mixing time, followed by additional 90 sec of wet mixing time. After batching the basal diets, they were proportionally blended to generate 4 kg batches ranging in crude protein from 16 to 24%. Two batches of each level of crude protein were generated, one of which was supplemented with a lignosulfonate pellet binder at 0.5% on top of the basal formulation. After recombining basal diets to get a crude protein range and after adding lignosulfonate, the individual batches were thoroughly mixed by hand in a clean bucket.

A laboratory scale pellet mill (Model CL-2, California Pellet Mill, Crawfordsville, IN) was employed for pelleting. The pellet mill was warmed to 180 °F before pelleting treatment batches. The pellet collection procedure was the same as described in *Trial 1*. The order in which treatments were pelleted was randomized by crude protein level to reduce the impact of continuously warming pelleting equipment on pellet durability. Pellet mill data collection and pellet durability testing was conducted in a manner similar to that described in *Trial 2*.

All data was analyzed using the GLM procedure of JMP 11.2 (SAS Institute, Cary, NC). Simple linear regression was employed with the crude protein variable set as a continuous factor and the lignosulfonate variable set as a nominal factor. Means were separated with the LSMeans procedure of JMP and considered statistically significant at $P \leq 0.05$ unless otherwise noted.

Results

Trial 1

The experimental diet is depicted in Table III-1. An interaction was observed between conditioned mash temperature and lignosulfonate ($P \leq 0.01$), as illustrated in Figure III-1. Lignosulfonate addition improved pellet durability index (PDI) by 22 points at the coolest pelleting temperature (164 °F), but by only 7 points at the hottest pelleting temperature (180 °F). Lignosulfonate addition improved PDI more at cooler temperatures than it did at warmer temperatures.

Trial 2

The experimental diets are shown in Table III-2. An interaction was observed between mixer added fat and lignosulfonate ($P \leq 0.01$), as depicted in Table III-4. Lingosulfonate addition improved PDI by over 22 points in the presence of 3% mixer added fat, but by only 11 points in the presence of 1.5% mixer added fat. Lignosulfonate improved PDI more in high fat diets than low fat diets. Particle size did not affect PDI, nor did it interact with any of the other factors.

Trial 3

The experimental diets are shown in Table III-6. As percentage crude protein increased, PDI decreased ($P \leq 0.01$). Lignosulfonate addition resulted in a consistent 7 point improvement in PDI at each level of crude protein ($P \leq 0.01$), as depicted in Figure III-2.

Discussion

Trial 1

It has been well established that an increased conditioning temperature of mash feed before pelleting increased pellet durability (Pfost, 1964; Thomas *et al*., 1997; Cutlip *et al*., 2008). It was also common for the effect of a factor known to be detrimental to pellet durability, such as high mixer added fat or a thin die, to be ameliorated by another factor known to positively affect pellet durability, such as high mash conditioning temperature or a slower production rate. Examples of this included the work of Loar *et al*. (2014) in which the negative effect of adding 2.18% fat on pellet durability was ameliorated by pelleting at a greater temperature.

In the current trial, similar interactions between positive and negative factors affecting pellet durability were observed (Figure II-1). Addition of lignosulfonate to a diet allowed pellet durability to be maintained while pelleting at lower conditioning temperatures. There was an apparent limit to the beneficial effect of lignosulfonate in the current trial. When pelleting conditions were optimized, there were limited possibilities to improve pellet durability. When pelleting conditions were poor, such with lower mash conditioning temperatures, other factors, such as lignosulfonate addition, improved pellet durability because there was an opportunity for improvement.

Lignosulfonate addition may provide the opportunity to improve pellet durability when low pelleting temperatures were necessary, but good pellet durability was still an objective. Examples of this would include pelleting diets with whey protein where maximum pelleting temperatures have rarely exceeded 165 °F or when heat labile ingredients were included in the feed formulation, such as exogenous enzymes.

Trial 2

The negative effect of mixer added fat on pellet durability has been well established (Thomas *et al*., 1998; Ghering *et al*., 2011; Fahrenholz, 2012; Corey *et al*., 2014; Loar *et al*., 2014). Several methods to ameliorate the negative impact of mixer added fat on pellet durability have also been demonstrated. These have included the use of a thicker die (Wamsley & Moritz, 2013) or increased mash conditioning temperatures (Loar *et al*., 2014). Another method used to reduce the negative impact of mixer added fat on pellet durability was through addition of lignosulfonate to the diet.

Winowiski (2015) demonstrated that 0.5% lignosulfonate addition negated the negative impact of 2% mixer added fat. A similar effect was observed in the current study where addition of 0.5% lignosulfonate in a 3% mixer added fat diet resulted in similar pellet durability as a diet without lignosulfonate and 1.5% mixer added fat (Table III-4). As a surface acting agent, lignosulfonate was apparently able to penetrate the hydrophobic layer created by high fat inclusions to induce sufficient hydrogen bonding at the outermost portion of the pellet, to result in enhanced pellet durability.

The concept behind including the particle size factor was that increased corn particle size would result in more surface area on the outer surface of the pellet where lignosulfonate could evidence its binding capabilities, but this was not observed.

Trial 3

Thomas *et al*. (1998) and Buchanan & Moritz (2009) explained that the protein content of feed impacted pellet durability. Starch and proteins were said to aid the "glass transition" on the outer surface of the pellet that contacted the hot die to form bonds during the pelleting process (Behnke, 2007). The current trial blended a low protein, high starch diet with a high protein, low starch diet in increments to evaluate the incremental effect of protein on pellet durability.

The incremental change in formulation either by increasing crude protein, or decreasing starch, negatively impacted pellet durability in the current trial (Figure III-2). In the mixed rations, corn and soy were the only ingredients that changed in proportion, making the effect of crude protein level as opposed to starch level difficult to separate. Addition of lignosulfonate resulted in a consistent improvement in pellet durability across all ranges of protein but did not improve pellet durability more in a high protein, low starch diet than a low protein, high starch diet. Perhaps a more suitable starting point for determining the effect of lignosulfonate with respect to specific nutrients would be pelleting ingredients high in protein or high in starch with and without lignosulfonate. This would allow determination of whether the increasing protein or decreasing starch was the reason for diminished pellet durability.

Conclusions

Marginal pelleting conditions, such as low conditioning temperature and high fat inclusion, were less detrimental to pellet durability when lignosulfonate was added. Lignosulfonate interacted in marginal pelleting conditions to improve pellet durability more in worst-case scenarios than best-case scenarios. The use of lignosulfonate would be beneficial if poor pellet conditions were inevitable and the improvement in pellet quality was certain to improve broiler live performance.

Table III-1. Composition of broiler starter diet with and without lignosulfonate (LS).

Ingredients	Control	LS
	(%)	
Corn	64.28	64.28
SBM (48% CP)	30.40	30.40
Poultry fat	2.00	2.00
Limestone	0.25	0.25
Defluorinated phosphate (18 % P)	1.91	1.91
Salt	0.28	0.28
DL-Methionine	0.18	0.18
L-Lysine	0.11	0.11
L-Threonine	0.09	0.09
Trace mineral premix[1]	0.20	0.20
Vitamin premix[2]	0.05	0.05
Choline chloride (60%)	0.20	0.20
Selenium[3] (0.06%)	0.05	0.05
LS	0.00	0.50
Calculated Nutrients		
Protein	20.00	
Calcium	0.85	
Available phosphorous	0.43	
Total Lysine	1.14	
Total Methionine + Cysteine	0.82	
ME, kcal/g	2988	

[1] Mineral premix provided the following per kg of diet: Mn, 120 mg; Zn, 120 mg; Fe, 80 mg; Cu, 10 mg; I, 2.5 mg; Co, 1 mg.
[2] Vitamin premix provided the following per kg of diet: vitamin A, 6600 IU; vitamin D3, 1.980 IU; vitamin E, 33 IU; vitamin B12, 0.02 mg; biotin, 0.13 mg, menadione, 2 mg; thiamine, 2 mg; riboflavin, 6.6 mg; pantothenic acid, 11 mg; vitamin B6, 4 mg; niacin, 55 mg; folic acid, 1.1 mg.
[3] Selenium premix provided Se at 0.3 mg/kg of feed.

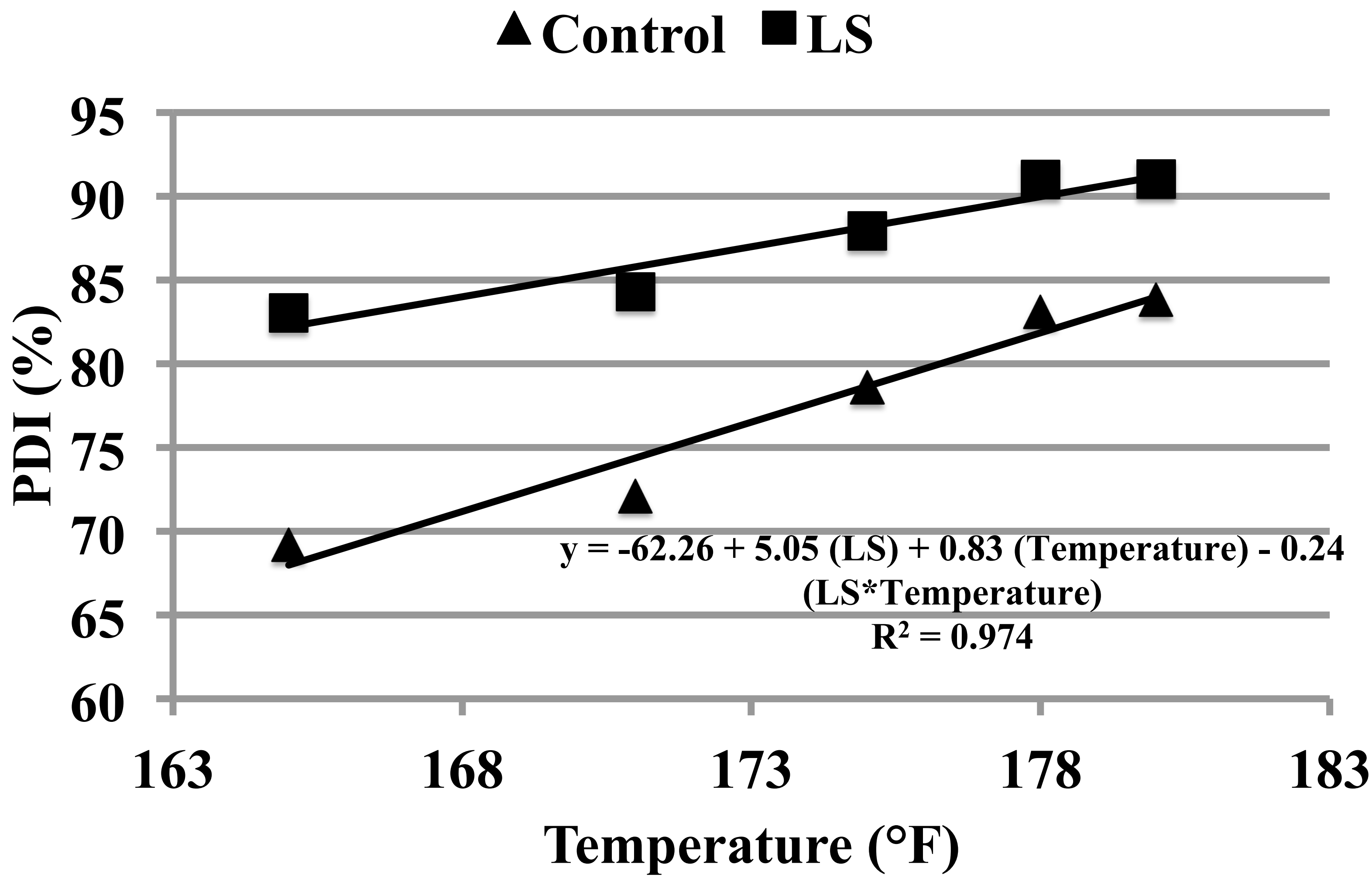

Figure III-1. Effect of lignosulfonate (LS) and temperature on pellet durability.

Table III-2. Composition of broiler finisher diet differing in corn particle size, mixer added fat, and lignosulfonate (LS).

	1.5% Fat				3.0% Fat			
	Fine Corn		Coarse Corn		Fine Corn		Coarse Corn	
Ingredients	LS	CON	LS	CON	LS	CON	LS	CON
	(%)							
Fine corn	69.31	69.31	55.81	55.81	67.81	67.81	54.31	54.31
Coarse corn	0.00	0.00	13.50	13.50	0.00	0.00	13.5	13.5
SBM (48% CP)	25.73	25.73	25.73	25.73	25.73	25.73	25.73	25.73
Poultry fat	1.50	1.50	1.50	1.50	3.00	3.00	3.00	3.00
Limestone	0.64	0.64	0.64	0.64	0.64	0.64	0.64	0.64
Dicalcium phosphate (18.5 % P)	1.48	1.48	1.48	1.48	1.48	1.48	1.48	1.48
Salt	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
DL-Methionine	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
L-Lysine	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
L-Threonine	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07
Trace mineral premix[1]	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Vitamin premix[2]	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Choline chloride (60%)	0.20	0.20	0.20	0.20	0.20	0.20	0.20	0.20
Selenium[3] (0.06%)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
LS	0.50	0.00	0.50	0.00	0.50	0.00	0.50	0.00
Calculated Nutrients								
Protein	18.12				18.00			
Calcium	0.70				0.70			
Available Phosphorous	0.35				0.35			
Total Lysine	1.01				1.01			
Total Methionine + Cysteine	0.73				0.73			
ME, kcal/g	3.01				3.08			

[1] Mineral premix provided the following per kg of diet: Mn, 120 mg; Zn, 120 mg; Fe, 80 mg; Cu, 10 mg; I, 2.5 mg; Co, 1 mg.

[2] Vitamin premix provided the following per kg of diet: vitamin A, 6600 IU; vitamin D3, 1.980 IU; vitamin E, 33 IU; vitamin B12, 0.02 mg; biotin, 0.13 mg, menadione, 2 mg; thiamine, 2 mg; riboflavin, 6.6 mg; pantothenic acid, 11 mg; vitamin B6, 4 mg; niacin, 55 mg; folic acid, 1.1 mg.

[3] Selenium premix provided Se at 0.3 mg/kg of feed.

Table III-3. Main effect of mixer added fat (MAF), corn particle size, and lignosulfonate (LS) on pellet durability index (PDI), pellet conditioning temperature, and pellet mill motor load.

MAF	Corn size[1]	Binder[2]	n	PDI	Temperature	Motor Load
(%)				(%)	(°F)	(Amps)
Main Effect						
1.5			12	79.28^{A}	176.97	5.24
3.0			12	57.90^{B}	176.73	5.16
P-value				0.001	0.836	0.279
	Fine		12	67.97	176.31	5.16
	Coarse		12	69.22	177.40	5.23
	P-value			0.433	0.350	0.370
		CON	12	60.19^{B}	176.60	5.16
		LS	12	77.00^{A}	177.10	5.23
		P-value		0.001	0.665	0.384
		SEM[4]		1.097	0.797	0.050

$^{A, B}$ Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Corn particle size in each finisher diet.
[2] The binder was LS powder added at a 0.5% inclusion on top of the base formulation.
[3]Pellet Durability Index was determined using NHP100 pellet tester set to 30-second interval.
[4] Standard error of mean (SEM) for n=12 samples of each main effect of MAF, corn size, and binder.

Table III-4. Two-way interaction effects of mixer added fat (MAF) and corn particle size, MAF and lignosulfonate (LS), and corn size and LS on pellet durability index (PDI), pellet conditioning temperature, and pellet mill motor load.

MAF	Corn size[1]	Binder[2]	n	PDI	Temperature	Motor Load
%				(%)	(°F)	(Amps)
MAF x Corn Size Interaction Effect						
1.5	Fine		6	80.32	176.44	5.23
1.5	Coarse		6	78.25	177.50	5.24
3.0	Fine		6	55.61	176.16	5.09
3.0	Coarse		6	60.19	177.30	5.22
P-value				0.051	0.974	0.420
MAF x Binder Interaction Effect						
1.5		CON	6	73.71[B]	177.15	5.24
1.5		LS	6	84.86[A]	176.79	5.23
3.0		CON	6	46.67[C]	176.05	5.09
3.0		LS	6	69.14[B]	177.41	5.23
P-value				0.003	0.459	0.303
Corn Size x Binder Interaction Effect						
	Fine	CON	6	58.80	175.33	5.12
	Fine	LS	6	77.13	177.29	5.21
	Coarse	CON	6	61.58	177.88	5.21
	Coarse	LS	6	76.87	176.92	5.25
	P-value			0.344	0.216	0.754
	SEM[4]			1.55	1.277	0.071

[A,B] Means within each column that possess different superscripts differ significantly ($P \leq 0.01$).
[1] Corn particle size in each finisher diet.
[2] The binder was LS powder added at a 0.5% inclusion on top of the base formulation.
[3]Pellet Durability Index was determined using NHP100 pellet tester set to 30-second interval.
[4] Standard error of mean (SEM) for n=6 samples of each possible two-way interaction of MAF, corn size, and binder.

Table III-5. Three-way interaction effect of mixer added fat (MAF), corn particle size, and lignosulfonate (LS) on pellet durability index (PDI), pellet conditioning temperature, and pellet mill motor load.

MAF	Corn size[1]	Binder[2]	n	PDI	Temperature	Motor Load
%				(%)	(°F)	(Amps)
MAF x Corn Size x Binder Interaction Effect						
1.5	Fine	CON	3	73.57	175.90	5.25
1.5	Fine	LS	3	87.07	176.99	5.22
1.5	Coarse	CON	3	73.85	178.40	5.24
1.5	Coarse	LS	3	82.65	176.59	5.24
3.0	Fine	CON	3	44.03	174.75	4.99
3.0	Fine	LS	3	67.20	177.59	5.19
3.0	Coarse	CON	3	49.30	177.36	5.18
3.0	Coarse	LS	3	71.08	177.24	5.26
P-value				0.602	0.991	0.583
SEM				2.194	1.595	0.100

[1] Corn particle size in each finisher diet.
[2] The binder was LS powder added at a 0.5% inclusion on top of the base formulation.
[3]Pellet Durability Index was determined using NHP100 pellet tester set to 30-second interval.
[4] Standard error of mean (SEM) for n=6 samples for each three-way interaction of MAF, corn size, and binder

Table III-6. Composition of broiler diets formulated at 16 and 24% crude protein.

Ingredients	16% Crude Protein[4]	24% Crude Protein[4]
	(%)	
Corn	73.96	54.35
SBM (48% CP)	20.62	40.33
Poultry fat	1.50	1.50
Limestone	0.74	0.74
Dicalcium phosphate (18.5 % P)	1.83	1.83
Salt	0.50	0.50
DL-Methionine	0.12	0.24
L-Lysine	0.16	0.00
L-Threonine	0.07	0.01
Trace mineral premix[1]	0.20	0.20
Vitamin premix[2]	0.05	0.05
Choline chloride (60%)	0.20	0.20
Selenium[3] (0.06%)	0.05	0.05
Calculated Nutrients		
Protein	16.00	24.00
Calcium	0.80	0.85
Available phosphorous	0.40	0.42
Total Lysine	0.90	1.33
Total Methionine + Cysteine	0.65	0.98
ME, kcal/g	3.05	2.84

[1] Mineral premix provided the following per kg of diet: Mn, 120 mg; Zn, 120 mg; Fe, 80 mg; Cu, 10 mg; I, 2.5 mg; Co, 1 mg.
[2] Vitamin premix provided the following per kg of diet: vitamin A, 6600 IU; vitamin D3, 1.980 IU; vitamin E, 33 IU; vitamin B12, 0.02 mg; biotin, 0.13 mg, menadione, 2 mg; thiamine, 2 mg; riboflavin, 6.6 mg; pantothenic acid, 11 mg; vitamin B6, 4 mg; niacin, 55 mg; folic acid, 1.1 mg.
[3] Selenium premix provided Se at 0.3 mg/kg of feed.
[4] The diets were blended together to generate a crude protein profile ranging from 16 to 24% in 1% increments, thus generating nine diets differing in percentage crude protein. Each percentage crude protein diet remained as is for a control or was amended with 0.5% lignosulfonate (LS).

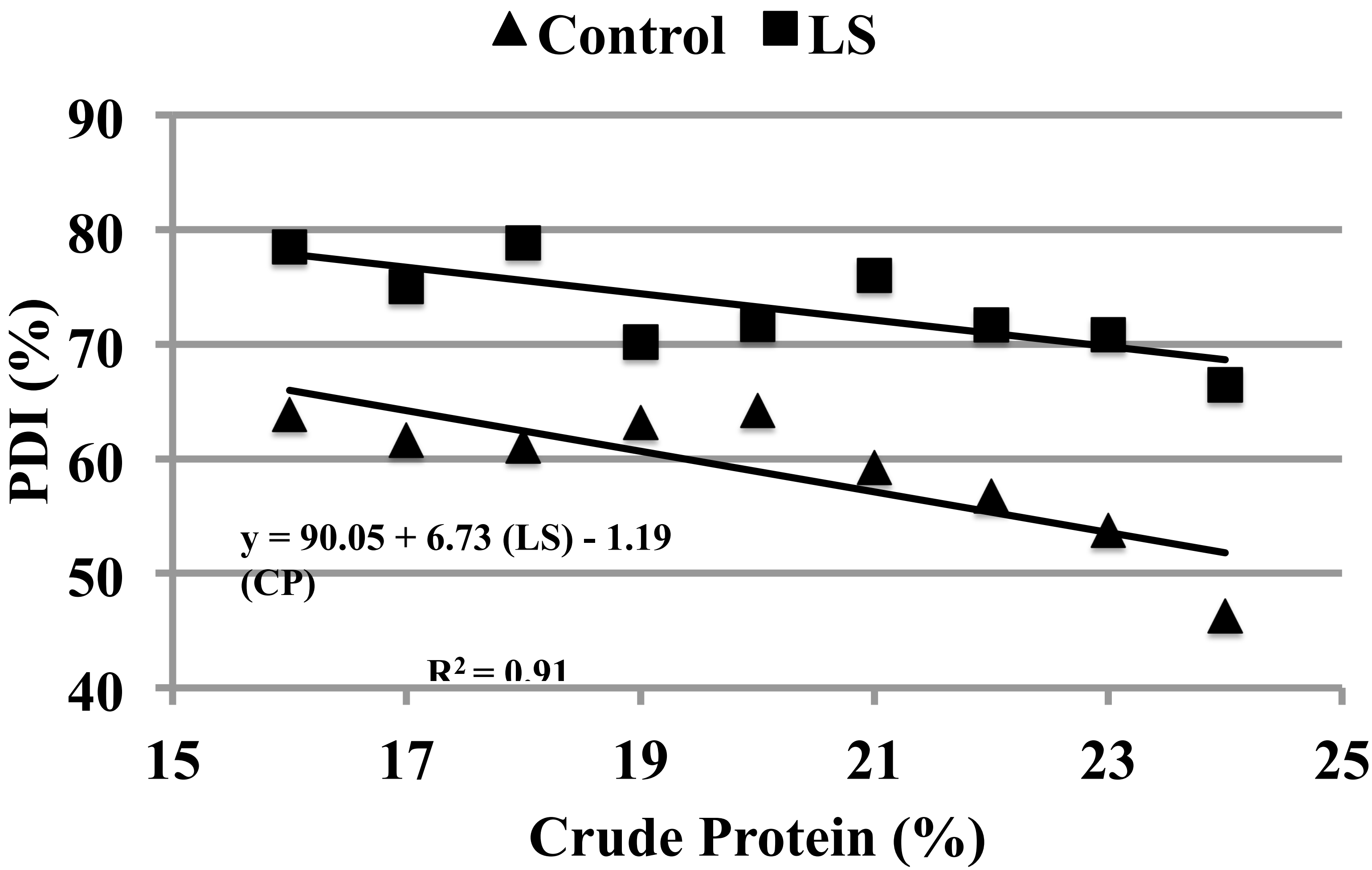

Figure III-2. Effect of lignosulfonate (LS) and percentage crude protein on pellet durability.

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FINAL CONCLUSIONS

The goal for any animal producer is to produce animal protein as efficiently as possible. Efficient production of meat provides consumers with an affordable and nutritious protein source. Improved efficiency in the rearing of broilers not only benefits consumers by keeping retail prices down, but also benefits producers and the reserves of resources required to produce broilers.

While several parts of the broiler integration model are manipulated to affect the efficiency of broiler operations, feed costs represent the largest monetary input in broiler live production. The feed mill is at the center of the monetary inputs, processing and handling the largest cost in live production. Thus, the feed mill is important to the efficiency of broiler production and has a significant impact on the efficiency of broiler grow-out.

There are several goals of integrated broiler feed manufacturers, but the end goals are to efficiently and sustainably produce broilers. While several factors are known to affect broiler FCR, feed particle size, pellet diameter, and pellet quality have a significant impact on broiler feed efficiency. While many producers include CC using conventional equipment, some feed mills may not have the infrastructure required to include CC in broiler feeds. Also, grinding equipment requires maintenance and is subject to malfunction. Thus, an alternative method to introduce CC to broilers would be beneficial to feed manufacturers. The CC and WC diets explained in Chapter I performed similarly, suggesting that WC could be used as a substitute for CC when necessary.

While previous research suggested that smaller diameter pellets were more suitable for broilers before 35 d, the study in Chapter I concluded that the impact of pellet diameter on broiler growth was most noticeable beyond 35 d. Larger diameter pellets allow broilers to consume feed more efficiently, especially after 35 d, because the broilers can grasp more feed with each visit to the feeder when compared to broilers consuming smaller diameter pellets.

Good pellet quality is imperative to the efficient rearing of broilers. PPLA systems are implemented to improve pellet quality while supplying the energy levels that broilers require for growth and maintenance. What is less understood is how liquids disperse in PPLA systems. As described in Chapter II, liquids preferentially coat fines when compared to pellets. This results in energy disparities between pellets and fines, with the latter containing more gross energy. Fat laden fines affect female broiler BW, making them heavier than females consuming fines that were not subjected to PPLA. If poor pellet quality is inevitable, post coating the pellets improves the growth of females or the birds most likely to be consuming fines.

Just as with grinding equipment, PPLA systems are not in every feed mill and are expensive to install. Sometimes they require maintenance and servicing as well. In these cases, an alternative to removing fat from the mixer to maintain pellet quality is desired. Lignosulfonate is a pellet binder that improves pellet durability. As described in Chapter III, including lignosulfonate in broiler diets manufactured at low mash conditioning temperatures or with high inclusions of mixer added fat significantly improves pellet durability over control diets. The use of lignosulfonate is another alternative method employed to maintain pellet quality, thus affecting the efficiency of broiler production.