Evaluation of Feed Manufacturing on Feed Quality, Performance, Nutrient Utilization and Carcass Characteristics of Broilers

by

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ABSTRACT

Previous studies have shown corn particle size and feed form manipulation influence broiler performance, gizzard development, nutrient utilization, and carcass characteristics. It is well-known that feeding pellets reduces feed wastage, mealtime, selective feeding, and nutrient segregation as well as increasing feed intake, weight gain, and feed efficiency. Prior to pelleting, feed is conditioned by injecting steam to the meal. The rise in temperature and moisture accomplished during feed conditioning reduces bacterial load, improves pellet quality, and increases production rate. However, high conditioning temperatures can negatively affect availability of thermolabile nutrients such as vitamins, amino acids, and exogenous enzymes. In trial 1, the effects of conditioning temperature were evaluated on growth performance, nutrient digestibility, and processing yields of broilers from 15 to 49 d of age. A total of 1,120 Ross x Ross 708 broilers was distributed among 4 treatments with 10 replicates per treatment and 28 birds/pen. Treatments consisted of 4 conditioning temperatures (71, 77, 82, and 88°C). A common starter was fed as crumbles, whereas grower and finisher feeds were fed as whole pellets. Titanium dioxide was added as an indigestible marker (0.5%) during the grower phase from 15 to 28 d to determine nutrient digestibility. Feed intake and BW gain were determined at 14, 28 and 49 d of age and FCR was corrected for mortality. At 50 d of age, 10 birds/pen were processed to determine carcass and parts weight and yield. Increasing conditioning temperature from 71 to 88°C increased ($P<0.05$) pellet quality and reduced ($P<0.05$) percentage of fines. Feed intake, BW gain, and FCR were unaffected by conditioning temperatures. Tender weights

were heavier ($P<0.05$) on birds fed diet conditioned at 82°C and lowest at 77°C. Increasing conditioning temperatures from 77 to 82°C caused a reduction ($P<0.05$) in apparent ileal digestibility of crude protein and ileal digestible energy of 4.88%, and 106 kcal/kg, respectively. A second study was conducted to evaluate the interactive effects of feed form and corn particle size necessary to optimize growth performance, carcass yield, and nutrient utilization of broiler. A factorial arrangement of 3 × 3 consisting of 3 corn particle sizes (750, 1,150 and 1,550 µm) and 3 feed forms (mash, 3- and 4-mm pellets) were provided to broilers from 1 to 39 d. Titanium dioxide (TiO_2) was added as an indigestible marker (0.5%) during the finisher phase (27-39 d) to determine nutrient digestibility. Feed intake (**FI**) and body weight (**BW**) were determined at 17, 27 and 39 d of age and FCR was corrected for mortality. On d 40, 10 birds per pen were processed to determine carcass and parts weight and yield. Broilers fed 3- and 4-mm pellets had higher BW, FI, and lower FCR ($P<0.05$) than broilers fed mash diets at 39 d of age. Broilers fed diets with 750 µm corn particle size had higher ($P<0.05$) BW and FI than broilers fed diets with 1,550 µm corn particle size at 39 d. Feed efficiency at 39 d of age was unaffected by corn particle size. Broilers fed 3 mm pellets had the heaviest ($P<0.05$) carcass and breast weights, followed by 4 mm pellets and lightest weights exhibited by broilers fed mash diets. Broilers fed diets with 750 µm corn particle size had heavier carcass and breast weights ($P<0.05$) than broilers fed diets with 1,550 µm. Digestibility of nutrients was enhanced by pelleting particularly when corn particle size increased. These results demonstrated that feed processing parameters such as conditioning temperatures, particle size, and feed form influence feed quality, broiler performance, nutrient digestibility, and carcass characteristics. These parameters ease the feed manufacturing process while simultaneously improving growth performance and increasing meat yield of broilers.

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I. INTRODUCTION

Grinding represents the second largest energy expenditure after pelleting and potential reductions in grinding costs by increasing corn particle size in poultry diets can help in electric energy savings and potential improvements in nutrient digestibility. Feed form can influence feed intake and overall broiler growth performance (Dozier et al., 2010). Pelleted diets have been utilized to reduce feed wastage, mealtime, selective feeding, and nutrient segregation as well as to increase feed intake, BW gain, bird uniformity, resting time, and feed efficiency (Behnke, 1996). However, it is important to maintain a balance during the conditioning process prior to pelleting as low temperature can result in poor pellet quality and higher energy consumption while high temperatures can reduce the digestibility of thermolabile nutrients. High quality pellets are often well accepted by poultry producers, but feed manufacturers often seem to struggle to not sacrifice nutrient availability over feed quality. Many researchers have reported that pelleting broiler diets results in higher BW and lower FCR than broilers fed mash diets. However, the effect of pellet diameter has been overlooked. Optimization of corn particle size and feed form in broiler diets can potentially reduce the environmental impact by improving nutrient digestibility and reducing nutrient excretion in litter coupled with improved animal health due to less ammonia and CO_2 levels in poultry houses and a reduction in the overall carbon footprint. Reduction in feed costs can also increase the affordability of poultry products. A better understanding of the interactive effects of feed form, corn particle size, and pellet diameter is necessary to optimize growth performance, carcass yield, and nutrient utilization of modern broiler strains. Results from this research will contribute to establish a closer relationship between feed manufacturing and applied nutrition, to optimize the genetic potential of broilers.

II. LITERATURE REVIEW

FEED MANUFACTURING BASIC OPERATIONS

Grinding

Cereal grains are subjected to a particle size reduction prior to their incorporation in animal feeds (Behnke, 1996). Particle size reduction make grains more suitable for animal feeding and digestion by improving mixing, handling and pelleting, as well as increasing surface area for improved digestive enzyme activity (Behnke, 1996; Koch, 1996). During grinding the cell wall of the aleurone layer is disrupted, which improves availability of nutrients bound in the nutrient matrix (Saunders et al., 1969; Oghbaei et al. 2016). For the broiler industry, grinding constitutes the second greatest energy cost after pelleting (Reece et al., 1985). Grinding costs and particle size are inversely correlated and grinding cost increases as particle size decreases (Stark, 2012). Indeed, fine grinding not only increases energy costs, but reduces grinding capacity, which can cause dust problems, and increase ingredient and feed bridging (Koch, 1996; Goodband et al., 2002).

Two main mills used for grinding are hammermills and roller mills. Hammermills are the preferred method of grinding due to their high grinding capacity, and ease of operations (Reece et al., 1985). Particle size reduction in a hammermill occurs as a result of impaction/attrition between rapidly moving hammers and relatively slow-moving feed ingredients (Koch, 1996). In a hammermill, particle size is determined by tip speed, screen size, hammer pattern as well as air assisting systems (Fang et al., 1997). Hammermill performance can be affected by motor horsepower, screen area, hammer tip speed, screen clearance, number of hammers, peripheral speed, diameter of screen opening, and others (Stevens, 1960; Fang et al., 1997). Smaller screen sizes increase collisions per particle, which results in a reduction of the maximum particle size exiting the grinder and an increased amount of fines (Yancey et al; 2014). Peripheral speed refers to; tip speed of hammers and not the revolutions per minute (rpm) of the motor (Pfost, 1970). Velocity or tip speed of hammers is critical for proper size reduction, it can be calculated by multiplying the rotational speed of the drive source (shaft rpm) by the hammer tip arc circumference (Koch, 1996). Tip speeds commonly range between 16,000 and 23,000 feet per minute (fpm) (Koch, 1996). In general, larger screen sizes and low tip speed (< 13,000 fpm) require less energy and offer opportunities for energy savings during grinding (Hamilton and Proudfoot, 1995).

With roller mills, particle size reduction is achieved by compression or shear forces and particle size is controlled by rolls opening distance, number of roll pairs as well as number of grooves and corrugations in each pair of rolls (Koch, 1996). Since roller mills produce a more uniform particle size, they are typically used in mash diets as ground materials have better flowing characteristics compared to hammermills (Svihus et al., 2004a; Vukmirović et al., 2017). Roller mills are more energy efficient than hammermills but have a lower grinding capacity and are not suitable to grind fibrous materials or hulls. (Reece et al., 1985; Wondra et al., 1995).

Regardless of the grinding equipment used, particle size uniformity is very important as it can influence mixing uniformity, ingredient segregation after mixing, and bird performance (Amerah et al., 2007). Ingredients with widely varying particle sizes are more difficult to mix and large particles tend to segregate from smaller particles during subsequent handling after mixing (Martin, 1983).

Mixing

Mixing is one of the most critical operations in feed manufacturing (Behnke, 1996) and it can be defined as the blending of two or more ingredients. Its main objective is to guarantee animals receive their nutritional requirements in every bite (Zinn, 2004). Nutrient uniformity in a complete balanced feed is essential to optimize nutrient utilization and animal performance (Behnke and Beyer, 2002). Poor mixing uniformity can lead to poor animal performance due to nutrient segregation (Behnke, 1996). McCoy et al. (1994) evaluated effects of mixing uniformity on broiler performance and reported improvements in average daily gain, average daily feed intake, and lower feed conversion ratio (FCR) as diet uniformity increased from poor to intermediate. After mixing, diets are ready to be fed, however more than 90% of diets fed to broilers are pelleted in order to improve feed consumption, BW, and FCR. According to Thomas and Van der Poel (2020) the pelleting process is split up in three different operations, conditioning, pelleting and cooling.

Conditioning

Conditioning is the first step in the pelleting process. During conditioning, dry mash particles are heated and hydrated using steam, which softens feed particles and helps to extract natural binders present in feed ingredients, increase die lubrication and improves compaction during pelleting (Thomas and van der Poel 1996). Furthermore, water supplied by steam during feed conditioning serves as a lubricant to increase production rate and heat transfer to reduce bacterial load and improve feed hygiene (Skoch et al., 1981). Proper conditioning also helps to produce high durability pellets, while decreasing energy expenditure and die wear (Gilpin et al., 2002; Froetschner, 2006).

Typically, steam addition in the conditioner increases moisture content by 3 to 5% and its distribution in feed particles varies depending on their initial moisture content, level of moisture present at the surface, size of particles, and presence of surfactants (Bouvier and Campanella, 2014; Thomas and Van der Poel, 2020). Additionally, heat and water provided by steam alter starch and proteins in feed particles, making them more susceptible to the formation of solid bridges during pelleting and cooling (Thomas and van der Poel, 1996). The alterations in protein and starch are normally improved when retention time in the conditioning chamber is increased. These chemical changes produce proteins to denature and improve binding properties of feed particles holding them together (Smallman, 1996). Factors such as temperature and retention time during conditioning and water content can influence partial denaturation of proteins in feed (Thomas et al., 1998). Denaturation involves the breakdown of the three-dimensional structure of proteins (secondary, tertiary and quaternary structures) thereby changing the bioactivity of protein (Van Barneveld, 1993; Rakic, 2012). Upon cooling, proteins reassociate, and bonds are established between different feed particles. However, during high conditioning temperatures (>88°C) or extended retention time (>1 min), heat sensitive amino acids are prone to react with a free carbonyl group of sugar and lead to Maillard reaction making them unavailable for animal digestion (Van Barneveld, 1993; Hendriks et al., 1994; Shiv Nah, 2017). Lysine is highly prone to the Maillard reaction in free form as it contains 2 amino groups that react with sugar during processing, causing a loss in nutritional quality and palatability of feed (Shiv Nah, 2017).

During feed conditioning, the hydrophobic nature of fat may interfere with moisture penetration into feed particles (Thomas, 1998). Therefore, added fat (and to a lesser extent, fat enclosed in cell walls) acts as a lubricant between particles and pellet die-wall resulting in higher production rates, but reduced pellet quality (Thomas, 1998). Additionally, fat addition can influence other ingredients' properties, for instance, gelatinization of starch can be inhibited in the presence of lipids or delayed at high conditioning temperatures (Larsson, 1980; Eliasson, 1981). This may lead to weaker pellets, vulnerable to deterioration during handling and transportation.

As conditioning temperature increases, production rates are increased due to reduced friction between feed and die holes (Reimer and Beggs, 1993; Smallman, 1996). However, applying too much steam will impair production capacity and pellet quality and may lead to plugging the pellet mill (Winowiski, 1985). The use of “wet” steam (as steam with excess condensate) is less efficient than “dry” steam (as superheated steam) to reach the target conditioning temperature and leads to undesirable pelleting behavior resulting in a reduced production capacity and die plugging (Thomas and van der Poel, 2020).

Other benefits of the conditioning process are reductions of bacterial load and potential elimination of foodborne pathogens as well as improving drying of pellets in the cooler (Reimer and Beggs, 1993).

Pelleting

After the conditioning process, mash is transformed into pellets using a pellet mill. The pelleting stage is a continuous compaction process in which hot mash is pressed through a pellet die consisting of multiple openings (Thomas and van der Poel, 2020). As pellets are extruded, knives mounted on the inside of the die casting are used to cut the pellet at the desired length (Ziggers, 2003). According to Skoch et al. (1981), frictional heat increases as feed is extruded through the pellet die can cause starch gelatinization particularly in the surface of the pellet, which helps in achieving higher pellet hardness and durability. Diameter of die holes can also influence the degree of gelatinization and a smaller die-hole diameter typically leads to higher degree of gelatinization and improved pellet quality (Heffner and Pfost, 1973). Furthermore, die thickness influences frictional heat increments and the length to diameter ratio alters particle binding.

The distance between roller and die or “gap-size” also influences the pelleting process (Thomas, 1998). With an increasing gap-size, pellet hardness or durability will firstly increase, but it will be reduced thereafter (Thomas et al., 1997). An initial increase in pellet durability is attributed to a dense layer of material emerging as a result of increased shear and prolonged pre-compression (Vukmirović, 2017). A further increase in clearance will result in decreased stability of feed mash on the edge of the rolls and die assembly, therefore leading to sideways 'leaking' of feed mash (Thomas et al., 1997), this in turn may account for the reduction in durability and increments in energy consumption.

Cooling

Pellets generally leave the pellet mill at temperatures ranging between 60 to 95°C and with moisture contents of 16 to 17.5%. (Robinson, 1970; Behnke and Gilpin, 2014). Heat and moisture added during conditioning must be removed by evaporation of the water and convection of heat from pellets to the cooling air in order to store pellets safely (Thomas, 1998). When cold air passes through pellets, the air temperature increases, this decreases relative humidity resulting in an increased air capacity to pick up moisture and heat removal from pellets (Shulman, 1959). Heat from steam and additional heat generated due to friction in the die are the driving forces in the water evaporation process of pellets (Thomas, 1998). During the cooling and drying stage, soluble components in feed recrystallize and create bonds between feed particles. After water evaporation occurs on the pellets’ surface, the pressure and heat gradient at the core of pellets provide migration of water and heat from the center to the outside of pellets (Thomas, 1998). Viscosity of some components will increase and aid in maintaining the structural integrity of pellets (Friedrich, 1964; 1977). Additionally, solid bonds between particles are established during the drying/cooling process (Thomas, 1998). Adjustments for a given bed depth can be done by modifying residence time and air-flow characteristics (Maier and Bakker-Arkema, 1992). It is very important to control air flow as excessive air-speeds can only dry the outer layer of the pellet causing cracks at the surface of the pellet and increasing their susceptibility to abrasion, negatively affecting pellet durability (Thomas, 1998). Additionally, pellet diameter can also influence the cooling process, pellets with a reduced diameter emit heat and moisture faster than large pellets.

DETERMINING PELLET QUALITY

Pellet Quality

Pellet quality is important to increase feed intake and reduce nutrient segregation after mixing and during transportation. Pellet quality can be expressed in terms of hardness and durability. Hardness is the force necessary to crush a pellet or a series of pellets at a time. Durability is the number of fines returning from pellets after being subjected to mechanical or pneumatic agitation (Thomas and van der Poel, 1996). According to Behnke (2014) pellet quality is mainly influenced by diet formulation, ingredient particle size, mash conditioning, feed rate, die compression ratio, L/D ratio, or cooling conditions. These factors are inter-related and aid in determining necessary modifications to optimize pellet quality, as pellet quality is highly important to bird's performance (Muramatsu et al., 2015).

Pellet durability represents the ability to handle pellets without experiencing unacceptable breakage or generating a significant percentage of fines (Stark and Fahrenholdz, 2015). Pellet durability index (PDI) was developed as a predictor of pellet fines produced during handling and transportation established by the American Society of Agricultural and Biological Engineers method S269.5 (ASABE, 2012). In the United States, pellet durability is determined by tumbling a sample of whole screened pellets (500 g) for 10 minutes at 50 rpm in a dust-tight enclosure. After tumbling, fines are screened using a wire sieve having openings just smaller than the nominal pellet diameter. Pellet quality is calculated using the following formula:

PDI = (Weight of pellets after tumbling/ Weight of pellets before tumbling) ×100

Holmen pellet tester is another method to analyze pellet quality and was mainly used in Europe and other regions where pneumatic transportation is more common. However, due to its faster results and smaller sample size needed for pellet quality analysis, it is gaining popularity in the United States. Holmen tester is a pneumatic method of measuring the durability of pellets and uses air to create abrasion of the pellets (Stark and Fahrenholdz, 2015). In this methodology, 100 g whole pellets are added to the testing chamber and agitated by forced air for 30, 60, 90, or 120 seconds. After testing, the sample is removed, weighed, and the percentage of whole pellets is calculated.

Use of indirect methods for predicting pellet quality is a useful quality control tool in feed mills. Results from this method can be used to adjust feed formulation, particle size, and pelleting conditions to improve feed quality delivered to birds and customers (Stark and Fahrenholdz, 2015).

EFFECT OF PARTICLE SIZE ON BROILER PERFORMANCE

Particle size of cereal grains influences feed digestibility, feed efficiency, mixing performance, and pelleting. Therefore, particle size evaluation is highly recommended by nutritionists and it is a necessary component of a feed manufacturing quality assurance program (Stark, 2012). A standard method for particle size analysis using dry sieving was published by ASABE (2009) (method S319.4). Average particle size has been reported as geometric mean diameter (GMD), and can be expressed as mm or microns (µm). Variation range is described by the geometric standard deviation (GSD), with a larger GSD representing lower uniformity

(Amerah et al., 2007). Both particle size and its uniformity are essential in determining their effects on broiler performance.

Birds recognize feed particles by its texture due to presence of mechanoreceptors in their beaks (Gentle, 1975). Broilers are known to prefer larger particles (Schiffman, 1968; Portella et al., 1988) and this preference is thought to increase with age (Nir et al., 1994b). Additionally, several authors have indicated that birds have a desire for structural components in diets, and will look for it in the environment if their diet has a low content of fibrous or other structural components (Hetland et al., 2005; Hetland and Svihus, 2007; Santos et al., 2008; Svihus, 2011). Fine particles have a greater surface area for steam penetration and particle binding during conditioning and pelleting, which yields higher pellet quality and results in greater exposure of digesta to digestive enzymes increasing digestibility (Reimer, 1992; Behnke, 2001). However, finely ground components in poultry diets are rapidly dissolved in the crop after consumption, which limits gizzard development by a lack of mechanical stimulation (Engberg et al., 2002; Svihus, 2011). Indeed, higher gizzard size and volume has been observed when structural components or large cereal particles are included in broiler diets (Engberg et al., 2002; Parsons et al., 2006; Amerah et al., 2008; Biggs and Parsons, 2009). Increase in gizzard size is a consequence of an increased grinding activity (Svihus, 2011).

To date, data regarding the effect of particle size on broiler performance are inconsistent. For instance, several authors have reported beneficial effects of fine particles in mash diets. In a study by Chewning et al. (2012), birds fed diets with a corn particle size of 300 μm had higher BW compared to birds fed with a corn particle size of 600 μm. Parsons et al. (2006) reported higher feed intake and FCR in birds fed mash diets with a corn particle size of 2,242 μm compared to other mash diets (781, 950 and 1,042 μm). Xu et al. (2015) reported lower feed intake, BW, and higher FCR when the inclusion of corn ground to 1,642 μm increased in broiler diets from 0 to 50%. Nir et al. (1994c) reported higher BW and lower FCR in birds fed diets with corn particle sizes between 1,130 to 1,230 μm, compared to birds fed corn particles of 2,020 to 2,110 μm. Killburn and Edwards (2001) reported increased performance and metabolizable energy (ME) when broilers were fed pelleted diets that included maize particle size of 869 μm compared to maize of 2,897 μm. Results of these research trials suggest that young chicks are not able to efficiently consume large particles due to an underdeveloped gizzard, which might increase time and energy expenditure for gizzard grinding (Lott et al., 1992; Xu et al., 2015).

Other researchers have reported improved performance when particle size of feed ingredients is larger. Amerah et al. (2007) reported that feeding birds with a greater corn particle size (1,164 vs 869 μm) improved weight gain and FCR. In a study by Reece et al. (1985), birds fed mash corn-based diets ground to 814 and 1,343 μm to broiler starters, reported better performance in birds fed diets with corn ground to 1,343 μm in terms of WG and feed efficiency. Nir et al. (1995) reported that broilers fed wheat and sorghum-based mash diets with particle sizes of 1,413 to 2,174 μm had heavier BW and higher feed efficiency compared to those fed diets ground to 628 to 681 μm. According to Svihus (2011), coarse particles enhance gizzard development and reverse peristalsis, which increases digesta retention time and gut reflux. Increased refluxes of digesta from the duodenum to gizzard improves nutrient digestibility (Svihus and Hetland, 2001; Amerah et al., 2007). Optimum particle size varies with the rate of development of the digestive system and beak dimensions (Portella et al., 1988). Research suggests that particles sizes >800 μm are advantageous for improving the performance of broilers fed mash diets. These beneficial effects are more pronounced in diets with better particle size uniformity.

Gastrointestinal tract development

Gastrointestinal tract development of poultry, specifically gizzard is greatly influenced by particle size (Amerah et al., 2007). Gizzard is a large and muscular organ adapted to a large quantity of hard and durable feed particle in their diet (Svihus, 2011). Gizzard reduces feed particle size, mixes digesta content with digestive enzymes, increases reverse peristalsis, and reduces passage rate of feed in the gastrointestinal tract (Duke, 1992). Lack of structural material for grinding can negatively affect gizzard development and reverse peristalsis (Amerah et al., 2007). In addition, broilers fed finely ground diets will experience reduced grinding activity in the gizzard, and with a reduced grinding activity, the gizzard will act as a transit organ rather than a grinding organ. Feeding broilers, a finely ground diet can lead to small underdeveloped gizzards and large proventriculus (Cummings, 1994; Taylor and Jones, 2004).

Several authors have reported increased relative gizzard weight in birds fed coarse particles (Parsons et al., 2006; Pacheco et al., 2013; Singh et al., 2014). Nir et al. (1994b) reported a positive correlation between feeding coarse particles and increased gizzard weight. Naderinejad et al. (2016) reported increased relative gizzard weight with birds fed corn ground to 651 and 796 µm vs corn particle size of 490 µm. Additionally, the authors observed a reduced pH in birds fed pelleted diets with corn ground to 796 µm compared to birds fed pelleted diets with corn particle size of 490 µm. The reduction on pH is important as it stimulates gastric function, supported by an increased secretion of HCl with coarser particles (Engberg et al., 2002; Naderinejad et al., 2016). Similarly, Amerah et al. (2008) reported a higher relative gizzard weight in birds fed corn ground to 528 µm vs 297 µm. Previous research reported that coarse particles (>850 µm) of wheat decreased pH of gizzard contents by an increased reverse peristalsis. A lower pH in the gizzard can help to inactivate pathogenic bacteria like *Salmonella* and *Clostridium perfringens* before entering the small intestine (Engberg et al., 2002)

Small intestine relative length has been reported to be shorter when dietary particle size increases (Amerah et al., 2008; Lv et al., 2015). However, other studies reported no influence of particle size on gastrointestinal tract length and weight (Naderinejad et al., 2016). Additionally, Rezaeipour et al. (2014) reported no difference in pancreas relative weight with birds fed coarse corn (6 mm) and fine grinding (3 mm).

Nutrient Digestibility

Particle size reduction increases surface area of digesta for digestive enzyme activity which improves nutrient digestibility. However, studies evaluating the influence of particle size on nutrient digestibility are limited. Bozkurt et al. (2019) reported increased total tract digestibility of ether extract, crude protein (CP), and higher pancreatic amylase activity in pullets fed coarse ground diets (1,096 and 1,122 µm) compared to fine ground diets (691 and 692 µm). In contrast, Singh et al. (2014) reported no effect of coarse corn (1,172 µm) inclusion on ileal digestibility of dry matter, nitrogen, and starch. In contrast, Cordova-Noboa et al. (2020) reported higher starch digestibility in birds fed diets containing corn ground to 838 µm compared to birds fed diets with corn ground to 418 µm. Similarly, Pacheco et al. (2013) reported higher protein digestibility in birds fed diets containing SBM ground to 1,290 µm compared to birds fed diets with SBM ground to 470 µm.

Several authors have reported increased metabolizable energy (ME) (Killburn and Edwards, 2001) and digestible energy (DE) (Lyu et al., 2010) when particle size of feed ingredients was reduced. Authors attribute this effect to greater surface area available for enzyme activity. In contrast, increased GE (Mtei et al., 2019) and starch digestibility (Ruhnke et al., 2015; Cordova-Noboa et al., 2020) with larger particles has been reported in both mash and pelleted diets. Killburn and Edwards (2001) reported increased Ca and phytate P retention as corn particle size increased from 869 to 2,897 µm. Similarly, Mtei et al. (2019) reported increased Ca digestibility and N retention in birds fed diets with corn ground to 642 and 818 µm compared to diets with corn particle size of 477 µm.

Higher nutrient digestibility observed in diets containing a greater percentage of coarse particles has been attributed to an increased grinding activity of the gizzard, as well as greater reverse peristalsis leading to higher digestion and absorption of nutrients (Svihus, 2011). Previous authors suggest that ingredient particle size effect on nutrient utilization is influenced by age and feed form (mash vs. pellets). Data from several authors, indicate that particle size is more critical in mash diets than in pelleted or crumbled diets, as birds prefer coarse particles, and these can't be distinguished in crumbled or pelleted diets (Chewning et al., 2012; Lv et al., 2015; Mohammadi Ghasem Abadi et al., 2019).

EFFECT OF FEED FORM ON BROILER PERFORMANCE

Modern meat type broilers have an increased appetite, which requires a higher nutrient density and feed quality to reach their genetic potential (Abdollahi et al., 2014). Feed form is highly important in modern meat yield broilers as it influences performance and nutrient digestibility. Mash is a complete ration that is usually finely ground and mixed so birds cannot easily select coarse particles. Mash diets are more economical to produce as they do not require any further processing after mixing (Jafarnejad et al., 2010). If mash diets are fed, mash quality should be assessed by size and uniformity of its particles. Proudfoot and Hulan (1989) observed lower incidence of sudden death syndrome (SDS) in broilers fed mash diets compared to broilers fed crumbled or pelleted diets, which was likely due to lower growth rate. In a study by Mendes et al. (1995), birds fed mash diets had a lower FCR than birds fed pelleted diets. However, birds consuming mash diets had lower feed intake, which resulted in lower BW gain (Calet, 1965; Choi et al., 1986; Nir et al., 1994a, b, 1995).

Increased feed intake of broilers fed pelleted diets over mash diets is mainly due to the ease in feed prehension and reduced feed wastage (Abdollahi et al., 2013b). The size of the pellet should be adequate to the size of the oral cavity to minimize energy expenditure in prehension, which can reduce time spent at the feeder and feed competition (Jensen et al., 1962; Reddy et al., 1962; Savory, 1974).

Additional benefits of pelleting include a higher digestibility of nutrients. Pelleting may expose feed components more efficiently to enzymatic degradation by denaturation of protein (Calet, 1965). However, pellet quality and level of fines is important as poor-quality pellets can be detrimental on bird performance (Dozier et al., 2010). During pelleting, high conditioning temperatures can reduce nutrient digestibility (Abdollahi et al., 2010; Lundblad et al., 2011; Loar et al., 2014), lead to formation of indigestible starch-protein and starch-lipid complexes, and increase digesta viscosity in diets with high content of non-starch polysaccharides. These observed effects could inhibit nutrient absorption in the small intestine (Creswell and Bedford, 2006; Teixeira Netto et al., 2019).

Pelleting has become one of the most common and popular hydro-thermal process in broiler diet preparation worldwide (Aguzey et al., 2018). It is an expensive process, but considering the amount of improvement in performance, its cost can be justified (Aguzey et al., 2018).

Gastrointestinal tract development

Feed form can influence gastrointestinal development. Birds fed mash diets typically have greater gizzard development than birds fed pelleted diets. Additional grinding that occurs as feed is compressed between the rolls and the die might explain the lower gizzard development typically observed in pelleted diets (Engberg et al., 2002; Svihus et al., 2004b; Svihus, 2011). After deglutition of feed, pellets are moistened and dissolved rapidly in the crop exposing their microstructure (i.e., particle size within the pellet), which is important for gizzard development (Svihus, 2011). Due to rapid dissolution of pellets after consumption, the macrostructure and pellet quality has an influence on feed consumption, but not in gizzard development (Svihus, 2011). Pelleted diets have a finer microstructure due to the grinding effect of the rolls in the pellet mill (Engberg et al., 2002; Svihus et al., 2004b; Svihus, 2011). Previous experiments have shown that mash feeding increases the weight of the digestive tract (Choi et al., 1986) and the length of the jejunum and ileum (Nir et al., 1994b) in broiler diets. According to Aguzey et al. (2018), birds fed pelleted diets have lower length and weight of duodenum, jejunum, ileum and caeca than those fed mash diets but villus height and crypt depth of birds fed pelleted diets are greater than broilers fed mash diets.

Nutrient Digestibility

Data regarding the effect of feed form on nutrient digestibility is still controversial. Naderinejad et al. (2016) and Abdollahi et al. (2018) reported that pelleting reduced coefficient of apparent ileal digestibility (CAID) of nitrogen in comparison to mash diets. Other authors have reported that pelleting did not affect CP or CAID of N (Abdollahi et al., 2013a; Singh et al., 2014; Ruhnke et al., 2015; Naderinejad et al., 2016). In contrast, Parsons et al. (2006) reported improvements in N and lysine retention when birds were fed hard pellets (0.2% of a commercial binder and manufactured at 5 to 6 ton/h) compared to soft pellets (2.5% of tap water inclusion and manufactured at 5 to 7 ton/h). Increased CP digestibility in pelleted diets could be explained by the degree of protein denaturation involving the breakdown of the three-dimensional structure, changing the bioactivity of the protein during thermal processing (Rakic, 2012). An increased breakdown of the aleurone layer cell walls makes protein more accessible to digestive enzymes (Saunders et al., 1969). A degree of protein denaturation occurs during pelleting (Skoch et al., 1981, 1983; Stevens, 1987; Reimer and Beggs, 1993; Behnke, 1996) making proteins more susceptible to breakdown and digestion.

Abdollahi et al. (2013b) reported improved CAID of fat by pelleting compared to mash diets. Bozkurt et al. (2019) reported increased ether extract digestibility in egg-laying pullets fed crumbles compared to mash diets, supported by an increment in pancreatic lipase activity. In contrast, Ege et al. (2019) reported no effect in fat digestibility when laying hens were fed crumbles or mash diets. Differences observed between studies can be influenced by bird type, age, nutritional composition of feed, fat/oil quality, and source. However, fat digestibility was likely improved by disruption of ingredients' cell wall during pelleting which caused a greater exposure of cellular content to bile acids and digestive lipases (Abdollahi et al. 2013b; Naderinejad et al., 2016).

Effect of feed form on the digestibility of starch and AME have also been evaluated (Amerah et al., 2007; Abdollahi et al., 2014; Ruhnke et al., 2015), but the results have been inconclusive. Killburn and Edwards (2001) reported an increase in apparent digestibility of ME in pelleted compared to mash diets, which can be explained by an increased intake of digestible energy as well as thermal modification of starch and protein due to pelleting. Nevertheless, some researchers have attributed improvements in AME to heavier gizzard weights (Svihus et al., 2004a; Naderinejad et al., 2016) rather than by higher starch gelatinization from the pelleting process.

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III. EFFECT OF CONDITIONING TEMPERATURE ON PELLET QUALITY, PERFORMANCE, NUTRIENT DIGESTIBILITY, AND PROCESSING YIELD OF BROILERS

ABSTRACT

Prior to pelleting mash is steam conditioned to increase starch gelatinization, protein gelation, production rate, and pellet quality. Conditioning reduces bacterial load and improves physical quality of feed. However, high conditioning temperatures can negatively affect availability of thermolabile nutrients such as vitamins and amino acids. This study was conducted to evaluate the effect of conditioning temperature on growth performance, nutrient digestibility, and processing yields of broilers from 15 to 49 d of age. A total of 1,120 Ross x Ross 708 broilers was randomly distributed among 4 treatments with 10 replicates per treatment and 28 birds/pen. Treatments consisted of 4 conditioning temperatures (i.e., 71, 77, 82, and 88^{o}C). A common starter was fed as crumbles, whereas grower and finisher feeds were fed as whole pellets. Titanium dioxide was added as an indigestible marker (0.5%) during the grower phase from 15 to 28 d to determine nutrient digestibility. On d 28, 4 birds per pen were selected and ileal digesta was collected to calculate fat, protein, and energy digestibility. Feed intake, BW gain, were determined at 14, 28, and 49 d of age and FCR was corrected for mortality. At 50 d of age, 10 birds/pen were processed to determine carcass and parts weight and yield. Data were statistically evaluated using ANOVA procedure and means were separated by Tukey's HSD test. Increasing conditioning temperature from 71 to 88°C increased ($P<0.05$) pellet quality and reduced ($P<0.05$) percentage of fines. Feed intake, BW gain, and FCR were not affected by conditioning temperatures. Tender weights were heavier ($P<0.05$) on birds fed the diet

conditioned at 82°C and lowest at 77°C. Increasing conditioning temperatures from 77 to 82°C caused a reduction ($P<0.05$) in apparent ileal digestibility of crude protein, and ileal digestible energy of 4.88%, and 106 kcal/kg, respectively. From these results, we conclude that increasing conditioning temperatures can negatively affect nutrient digestibility, however performance remains unaffected possibly by improvements in pellet quality.

INTRODUCTION

Pelleting involves agglomeration of mash into large compact particles through a mechanical process using heat, moisture, and pressure (Falk, 1985). Pelleting decreases bacterial load and nutrient segregation after mixing while increasing starch gelatinization and protein denaturation (Skoch et al., 1981, 1983; Stevens, 1987; Reimer and Beggs, 1993; Behnke, 1996). Pelleted diets also reduce feed wastage, selective feeding, and increase bird uniformity (Behnke, 1994). According to Reimer (1992), pellet quality is influenced by diet formulation, particle size, conditioning, die specifications, as well as cooling and drying. During pelleting, conditioning is the most important factor that influences pellet quality, although it is frequently overlooked and not fully understood.

Conditioning temperature is mainly influenced by ingredient characteristics and inclusion level and it typically varies between 76.7 and 93.3°C among feed mills (Cutlip et al., 2008). Steam injected during conditioning increases; moisture and temperature of mash which results in softening of feed particles, while also reducing friction in the pellet die leading to increased production rates (Skoch et al., 1981). However, high conditioning temperatures can reduce nutrient digestibility (Abdollahi et al., 2010a; Lundblad et al., 2011; Loar et al., 2014), lead to the formation of indigestible starch-protein and starch-lipid complexes and increase digesta viscosity in diets with high content of non-starch polysaccharides potentially inhibiting nutrient absorption in the small intestine (Creswell and Bedford, 2006; Teixeira et al., 2019). Special consideration must be given when evaluating the influence of conditioning temperatures on both nutrient availability and feed quality. Therefore, this study was conducted to evaluate the effect of conditioning temperature on pellet quality, growth performance, nutrient digestibility, and processing yields of broilers from 15 to 49 d of age.

MATERIALS AND METHODS

All procedures involving live birds were approved by Auburn University Institutional Animal Care and Use Committee (PRN 2018-3238).

Birds and Housing

A total of 1,120 d-old male broilers Ross × Ross 708 (Aviagen Inc., Huntsville, AL) obtained from a commercial hatchery was weighed, and randomly allocated to 40 floor pens. All floor pens were 1.5 m × 2 m (28 birds/pen; 0.10m^2/bird) in an environmentally controlled house. Birds and feed were weighed to determine feed intake (FI), body weight gain (BWG), and feed conversion ratio (FCR) at 1, 14, 28, and 49 d of age. The facility was a solid-sided house with a negative-pressure ventilation system. It was equipped with exhaust fans, forced-air heaters, cooling pads, and an electronic controller to manage temperature and ventilation. Feed and water were offered *ad libitum* with 1 tube feeder and 5 nipple drinkers per pen. The lighting program consisted of 23L:1D from d 1 to 7, 21L:3D from d 8 to 21, and 16L:8D from d 22 to 49. Room temperature started at 34°C from d 1 to 2, 31.3°C from d 3 to 5, 29.4°C from d 6 to 14, 28.3°C from d 15 to 23, 26.7ºC from d 24 to 28, and 23.8ºC from d 29 to 49. Housing conditions and mortality were monitored daily.

Feed Formulation, Manufacture and Experimental Design

Experimental diets were identical in nutrient content and ingredient composition and only differed in conditioning temperature (Table 3.1). Treatments consisted of diets submitted to 4 conditioning temperatures; 71, 77, 82 and 88°C. A common starter diet was fed as crumbles from 1 to 14 d of age, whereas experimental grower and finisher diets were fed as whole pellets from 15 to 49 d of age. Whole corn was ground with a hammermill (Model 11.5 × 38, Roskamp Champion, Waterloo, IA) equipped with a 4.76-mm screen. After grinding, dry ingredients were blended for 150 s (30 s dry cycle and 120 s wet cycle) in a twin shaft mixer (Model 726, Scott Equipment Co., New Prague, MN) to produce mash diets. Subsequently, mash diets were conditioned at either 71, 77, 82, and 88°C with a retention time of 45 s and then pelleted with a 4.0 x 36 mm pellet die ring (Model 1112-4, California Pellet Mill Co., Crawfordsville, IN). In order to ensure diets were conditioned at the specified temperatures, the cooler opening was closed until pellets reach the target temperature. The conditioning temperatures were monitored on the computer controllers as well as in thermometers located between the conditioner and hygienizer. Once the target temperature was reached, the access to the cooler was cleared so that the pelleting process was finished. Pellets were cooled with ambient air in a counter-flow pellet cooler (Model CC0909, California Pellet Mill Co., Crawfordsville, IN). Starter feed was crumbled in a crumbler with manual roll adjustment (Model 624SS, California Pellet Mill Co., Crawfordsville, IN). During the grower phase, treatments (n=4) were randomly assigned to each pen. Each treatment had 10 replicate pens with 28 birds per pen. Titanium dioxide (TiO_2) was added as an indigestible marker to determine nutrient digestibility during the grower period from 15 to 28 d of age.

Measurements

Feed was manufactured 7 +/- 1 days prior to starting each growing phase and placed at the farm 2 to 3 days after manufactured. Five (22.7 kg) feed bags were collected during bagging at even intervals to evaluate the effect of conditioning temperature on moisture content, and pellet durability index (**PDI**). From each bag collected, moisture content samples were kept in cups, and PDI was analyzed the same day feed was manufactured. Pellet durability index was determined by the ASABE method S269.5 (ASABE Standards, 2012). For fines percentage, 5 d after feed was manufactured and placed at the farm, 5 bags were randomly selected from each treatment pallet and each selected bag was then sifted using a No. 6 American Society for Testing and Materials (ASTM) screen. Percentage of fines was calculated with the following equation:

$$\text{Fines \%} = (\text{Weight of fines after sifting} / \text{weight of feed bag before sifting}) \times 100$$

Samples for moisture content, were placed in cups prior to moisture content determination, then samples were oven dried to determine dry matter (DM) (method 934.01; AOAC International, 2006). Samples were collected the day feed was manufactured and 5 d afterwards. On d 5 after feed was manufactured, samples were collected in cups and before determining fines percentage.

Feed weigh back and BW were recorded per pen at 14, 28, and 49 d of age. Mortality was removed, weighed, and recorded twice daily, and their BW was used to adjust FCR. On d 28, 4 birds per pen were randomly selected and euthanized using CO_2 followed by cervical dislocation. Ileal digesta was collected (2 cm posterior of Meckel's diverticulum to the 2 cm anterior of the ileal-cecal junction) by gently squeezing out ileal contents in a manner that provided enough sample (10-12 g, after freeze dried) for digestibility analysis. Concentration of (TiO_2) as an indigestible marker was measured in grower diets and in each ileal sample collected per pen, it was used to calculate the digestibility of energy, fat, and protein.

On d 49, 10 birds per pen were randomly selected, wing banded, and marked with feed-grade dye. Feed was removed 10 h prior to processing, but birds had access to water during the feed removal period. On d 50, selected birds were loaded in coops and transported to the Auburn University Pilot Poultry Processing Plant. Broilers were electrically stunned, exsanguinated, scalded, picked and eviscerated mechanically and placed on ice. After processing, carcasses were chilled for 4 h in iced water at 4°C prior to determining chilled carcass weight. On d 51, chilled carcasses were deboned using stationary cones to determine meat yield. During deboning, breast fillets (*Pectoralis major*) and tenders (*Pectoralis minor*) were weighed to determine parts yield. Carcass yield was calculated in relation to live BW of birds, whereas parts yield was calculated as a percentage of chilled carcass weight.

Nutrient Digestibility Analyses

Ileal digesta samples were frozen, lyophilized, and ground. Experimental diets and ileal digesta were analyzed for gross energy (**GE**), crude protein (**CP**) and crude fat content. Diet and digesta samples were analyzed for CP by determining nitrogen content via the Dumas method (method 990.03; AOAC International, 2006) using a N analyzer (Rapid N Cube, Elementar Analysensyteme GmbH, Hanau, Germany) with CP being calculated by multiplying percent N by a correction factor (6.25). Gross energy was determined using an adiabatic bomb calorimeter (Parr, 6300, Parr Instruments, Moline, IL) standardized with benzoic acid. Crude fat concentrations were estimated by boiling samples in hexane (method 2003.06; AOAC International, 2006) in a fat extractor (Soxtec model number 2043, Foss North America, Inc., Eden Prarie, MN).

Titanium dioxide was included in feed at 0.5% as an indigestible marker, and diet and digesta TiO_2 concentrations were determined in duplicates following the procedures of Short et al. (1996). Apparent ileal digestibility (**AID**) of crude protein, fat, and energy were calculated using the following equation:

$$AID\ \% = \{[(Nutrient/TiO_2)_{diet} - (Nutrient/TiO_2)_{digesta}] / (Nutrient/TiO_2)_{diet}\} \times 100$$

were ($Nutrient/TiO_2$) = ratio of crude protein, fat or energy to TiO_2 in diet or ileal digesta. Energy digestibility (%) values obtained from this equation were multiplied by gross energy content of the feed to calculate apparent ileal digestible energy **(IDE)** in units of kcal/kg. Titanium dioxide concentration on diet samples ranged from 0.45 to 0.47%.

Statistical Analyses

Data were analyzed using a randomized complete block design with pen location as a blocking factor. Each treatment was represented by 10 replicate pens, with pen being the experimental unit. Data were analyzed as a one-way ANOVA using the GLM procedure of JMP software (SAS Institute Inc., Cary, NC) using the following model:

$$Y_{ij} = \mu + T_i + \varepsilon_{ij}$$

where Y_{ij} is the observed response of the broilers in the pen; μ is the is the overall mean; T_i is the fixed effect of conditioning temperature treatment; and ε_{ij} is the residual error when the pen was regarded as an experimental unit, $\varepsilon_{ij}\ N\ (0, \sigma_\varepsilon^2)$. Mean values among the 4 treatments were compared using Tukey's HSD procedure with statistical significance considered at $P \leq 0.05$ unless otherwise indicated.

RESULTS AND DISCUSSION

Feed quality parameters

Data for feed quality parameters is presented in Table 3.2. Pellet durability index (PDI) was improved ($P<0.05$) in both grower and finisher diets as conditioning temperatures were increased. Grower diets conditioned at 71 and 77°C resulted in pellets with lower pellet durability ($P<0.05$) compared to those conditioned at 82 and 88°C. In finisher diets, pellet durability was the highest ($P<0.05$) in diet conditioned at 88°C and lowest in diets conditioned at 71 and 77°C, with diet conditioned at 82°C being intermediate.

Percentage of fines was reduced in both grower and finisher diets as conditioning temperatures were increased. Grower diet conditioned at 71^{o}C had higher ($P<0.05$) percentage of fines in comparison to diets conditioned at 82 and 88^{o}C, but similar to diet conditioned at 77^{o}C. However, during the finisher period, diets conditioned at 71 and 77^{o}C resulted in higher ($P<0.05$) percentage of fines, compared to diet conditioned at 88^{o}C, but similar to diet conditioned at 82^{o}C. Data from this research agrees with previous studies, which reported that as conditioning temperatures increase, there is an improvement in pellet durability and reduction in percentage of fines (Skoch et al., 1981; Cutlip et al., 2008; Abdollahi et al., 2010b; Attar et al., 2017). According to Behnke (2001) natural adhesives found in feed ingredients are released during the conditioning and pelleting process, which contributes to adhesion of feed particles resulting in more durable pellets with lower percentage of fines. In addition, grower diets had higher pellet durability than finisher diets likely due to their higher protein content (19.7% vs. 17.4% crude protein). These results are similar to those reported by Briggs et al. (1999) and Stevens (1987), where feeds with higher protein content had greater pellet durability. Denaturation of protein involves the breakdown of the three-dimensional structure, which changes the bioactivity of the protein during the thermal conditioning process (Van Berneveld, 1993; Rakic, 2012). These proteins are re-associated during the cooling process forming solid bridges and re-forming bonds (i.e., covalent binding, electrostatic interactions, van der Waals forces, hydrogen bonds, and entropic factors) between feed particles, which leads to higher pellet durability (Katsuta et al., 1990).

Moisture content of grower and finisher diets increased as the target conditioning temperature increased (Table 3.3). In grower diets, diet conditioned at 77^{o}C had lower moisture content ($P<0.05$) compared to diets conditioned at 82 and 88^{o}C, but similar to diet conditioned at

71^{o}C. A similar pattern was observed in finisher feeds, diet conditioned at 77^{o}C had the lowest moisture content ($P<0.05$), while diet conditioned at 88^{o}C had the highest ($P<0.05$) moisture content, with diets conditioned at 71 and 82^{o}C as intermediates. Generally, for every 14°C increase in temperature, there is a 1% rise in the moisture content of the conditioned mash (Anon., 1984). Therefore, conditioning at 88^{o}C requires more steam addition to reach the target temperature. Results of this study indicate that changes in the target conditioning temperature merits changes in the cooling process (e.g. changes in pellet bed depth or air flow). Due to moisture contents above 12% in finisher diets, feed samples were taken when diets were placed at the farm and analyzed for moisture content to ensure feed quality was maintained, moisture in diets ranged from 10.92 to 11.92%. According to Johnson and Townsend (2009) and Blanco et al. (2016), feeds with more than 13% moisture could cause mold and fungi growth during storage. It is not recommended to store feeds with moisture content >12% for long periods of time as it can result in mold growth, insect infestation, and reduction of feed quality (FAO, 1980). Furthermore, moisture gain can negatively influence animal performance by diluting the nutritional content of feed and increase transportation costs (Moritz et al., 2001).

Broiler performance variables

Although PDI increased and percentage fines decreased as conditioning temperature increased, it did not influence ($P>0.05$) feed intake, BW gain, and FCR from 15 to 49 days (Table 3.4). In contrast to our findings, Abdollahi et al. (2010b) and Amerah et al. (2013) reported that improvements in PDI as conditioning temperatures increased led to improvements in growth performance of broilers. These authors stated that negative effects of conditioning at 90^{o}C (damage of heat-labile nutrients) may be overcome by the consumption of high-quality pellets. In the present study, improvements in PDI (12% increment) were not enough to improve broiler performance. The improvements in pellet quality might have been undermined by damage to heat-labile nutrients as conditioning temperatures increased, interfering with nutrient utilization, as reported by other authors (Silversides and Bedford, 1999; Creswell and Bedford, 2006; Kenny and Flemming, 2006).

Teixeira et al. (2019) evaluated 5 conditioning temperatures; 50, 60, 70, 80, and 90^{o}C on corn-soybean-based diets fed to broilers from 1 to 21 d of age. These authors reported a quadratic effect on BWG as birds fed diets conditioned at 60 and 70^{o}C had the highest weight gains. In another study, Selle et al. (2013) found that increasing conditioning temperatures from 65 to 95^{o}C in sorghum-based diets fed to broilers during the grower period linearly depressed FCR by 2.27% without influencing feed intake. Furthermore, Abdollahi et al. (2010b) found that conditioning temperatures of 65, 75 and 90^{o}C on maize and sorghum-based diets fed to broilers from 1 to 21 d of age influenced BW gain at 21 d of age, with the higher BW gains at 60 and 90^{o}C, and lowest at 75^{o}C. Several studies have reported that feed processing at high temperatures results in reduced performance likely due to loss and damage of thermolabile nutrients and increased intestinal viscosity resulting in an impairment of nutrient utilization that interferes with growth performance (Creswell and Bedford, 2006; Kirkpinar and Basmacioğlu, 2006; Abdollahi et al., 2010a; Beaman et al., 2012; Loar et al., 2014; Homan et al., 2019). Loar et al. (2014) conducted a study with conditioning temperatures of 74, 85 and 96^{o}C in combination with 2 levels of mixer-added fat (MAF) (1.00 and 2.18%) and found that FCR increased when MAF decreased and conditioning temperatures increased. According to these authors fat, can play an important role in preserving heat-labile nutrients if conditioning temperature is increased. Fat can also reduce the friction as the feed is compressed between the die and rolls and protect thermolabile nutrients at the expense of lower pellet quality. Variations in ingredient composition, retention time during conditioning and compression ratio of the pellet die could be some of the reasons for the different findings.

Processing

No significant responses were established for any of the processing parameters evaluated, excepting tender weight (Table 3.5). Broilers fed diets conditioned at 82°C had heavier tender weight (*P<0.05*) compared to broilers fed diets conditioned at 71 and 77°C, but similar to broilers fed diets conditioned at 88°C. Loar et al. (2014) reported that conditioning temperatures (74, 85 and 96°C) and mixer fat addition (1.00 and 2.18%) did not influence carcass characteristics. Similarly, Cutlip et al. (2008) reported no differences in breast yield and fat pad percentage of broilers fed diets conditioned at 82.2 and 93.3°C and steam pressured at 20 and 80 psi from 1 to 39 d of age. Based on the lack of response observed for BW gain and feed intake with varying conditioning temperatures, carcass characteristics were not affected. However, tender weight response to varying conditioning temperatures is unexpected, further research is needed to explain this finding.

Nutrient digestibility

Apparent ileal digestibility (**AID**) of crude protein (**CP**), and ileal digestible energy (**IDE**) were influenced by conditioning temperatures (P<0.05; Table 3.6). Apparent ileal digestibility of crude fat was not influenced (P>0.05) by conditioning temperatures, although it numerically ranged from 82.47 to 86.25%. Broilers fed the diet conditioned at 71°C resulted in the highest (P<0.05) AID of CP, compared to broilers fed diets conditioned at 77 and 82°C. Broilers fed diets conditioned at 71 and 88°C resulted in the highest (P>0.05) AID of GE compared to broilers fed diets conditioned at 77 and 82°C. Ileal digestible energy was reduced

(P<0.05) when conditioning temperatures were increased from 77 to 82^{o}C, unexpectedly IDE was the highest when feed was conditioned at 88^{o}C.

Liu et al. (2013) reported increased amino acid digestibility when increasing conditioning temperatures from 65 to 95^{o}C in sorghum-based diets. Teixeira et al. (2019) also reported increased digestibility coefficients of crude protein, starch and dry matter as conditioning temperatures increased from 60 to 90^{o}C. In birds fed maize-based diets, Abdollahi et al. (2010a) reported that increments in intake of digestible protein and apparent metabolizable energy (AME) were similar when diets were conditioned at 60 and 90^{o}C, but lower in diets conditioned at 75^{o}C. It is plausible that a slight increment in AID of CP at 88^{o}C might have been due to thermal processing increasing the breaking of cell walls of the aleurone layer due to physical stress from the pelleting process, making protein easily accessible to digestive enzymes (Saunders et al., 1969). Furthermore, steam conditioning at 88^{o}C may have helped in the softening of the cell walls prior to pelleting, resulting in a slight increment in AID of CP.

In contrast, Cutlip et al. (2008) reported that conditioning temperatures of 83.3 and 92.2^{o}C did not cause any changes in total amino acid digestibility (TAAD) when measured in cecectomized roosters. However, several studies have reported reduced nutrient digestibility when high temperatures are reached during feed processing, which may be due to degradation of heat-labile nutrients, formation of resistant starch, increased digesta viscosity and reduction of amino acids availability through the Maillard reaction (Beaman et al., 2012; Loar et al., 2014; Boney and Moritz, 2017; Homan et al., 2019).

Ileal digestible energy results are still unexpected and unclear, since findings do not follow a pattern similar to that of CP, and neither was it influenced by feed intake (P>0.05). Further research is needed to explain differences observed in IDE as conditioning temperatures increased. Reductions in nutrient digestibility have a quadratic behavior as conditioning temperatures are increased. Differences with other authors are due to different grains, manufacturing techniques and digestibility assays, however most of the results lead to similar conclusions, were nutrient digestibility is reduced as conditioning temperatures are increased.

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Table 3. 1 Ingredient and nutrient composition of dietary treatments fed to Ross × Ross 708 male broilers from 1 to 49 d of age.

Ingredients, % "as fed"	Starter	Grower	Finisher
Corn, 7.4% CP	61.10	64.30	70.05
Soybean Meal, 46.9% CP	22.95	20.45	16.75
Pet Food Grade, Poultry Meal	7.50	5.30	3.95
Distilled Dried Grains with solubles, 27.16% CP	5.00	5.00	5.00
Poultry Fat	0.45	1.50	1.50
Dicalcium Phosphate	0.85	0.95	0.90
Limestone	0.88	0.87	0.85
Titanium Dioxide	0.00	0.50	0.00
Salt 96%	0.25	0.27	0.29
DL-Methionine	0.30	0.25	0.21
L-Lysine HCl	0.21	0.21	0.21
Sodium Bicarbonate	0.10	0.11	0.11
Choline Cl-60 %	0.11	0.09	0.04
L-Threonine 98%	0.08	0.07	0.08
Trace-mineral premix[1]	0.08	0.06	0.04
Zoamix 25%[2]	0.05	0.05	0.00
Vitamin premix[3]	0.05	0.04	0.03
Calculated analysis, % (unless otherwise noted)			
AME_n kcal/kg	2,970	3,035	3,102
Crude Protein	22.14	9.67	17.44
Digestible Lys	1.18	1.05	0.92
Digestible TSAA[4]	0.92	0.82	0.73
Calcium	2.02	1.85	1.66
Available P	0.96	0.88	0.79

[1]Mineral premix include per kg of diet: Mn (manganese sulfate), 120 mg; Zn (zinc sulfate), 100 mg; Fe (iron sulfate monohydrate), 30 mg; Cu (tri-basic copper chloride), 8 mg; I (ethylenediamine dihydriodide), 1.4 mg; and Se (sodium selenite), 0.3 mg.

[2]Zoamix 25% include per kg of diet: Zoalene, 125 mg.

[3]Vitamin premix includes per kg of diet: Vitamin A (Vitamin A acetate), 18,7390 IU; Vitamin D (cholecalciferol), 6,614 IU; Vitamin E (DL-alpha tocopherol acetate), 66 IU; menadione (menadione sodium bisulfate complex), 4 mg; Vitamin B12 (cyanocobalamin), 0.03 mg; folacin (folic acid), 2.6 mg: D-pantothenic acid (calcium pantothenate), 31 mg; riboflavin (riboflavin), 22 mg; niacin (niacinamide), 88 mg; thiamin (thiamin mononitrate), 5.5 mg; D-biotin (biotin), 0.18 mg; and pyridoxine (pyridoxine hydrochloride), 7.7 mg.

[4]TSAA = total sulfur amino acids.

Table 3. 2 Pellet Durability Index (PDI) and percentage of fines, of pelleted diets subjected to different conditioning temperatures[1]

Conditioning Temperature, °C	PDI, %		Fines[2], %	
	Grower	Finisher	Grower	Finisher
71	88.42[b]	86.95[c]	12.28[a]	9.01[a]
77	88.45[b]	86.40[c]	8.05[ab]	7.95[a]
82	96.39[a]	89.27[b]	5.43[b]	6.32[ab]
88	98.15[a]	94.61[a]	3.50[b]	4.39[b]
SEM[3]	1.47	0.29	1.72	0.69
P-value	0.0001	0.0001	0.0137	0.0012

[a-c]Least square means within a column with different superscripts differ significantly ($P < 0.05$)
[1]Values are least square means of duplicates of 5 feed bags per treatment.
[2]Fines were determined by sieving 5 feed bags of 22.47 kg per treatment. Percentage of fines was calculated by weight of fines/initial weight of feed × 100.
[3]SEM= Standard error of the mean for conditioning temperatures.

Table 3. 3 Moisture content of grower and finisher pelleted diets subjected to different conditioning temperatures[1]

Conditioning Temperatures, °C	Moisture content, %		
	Grower FM[2]	Finisher FM	Finisher F[3]
71	10.98[ab]	12.86[bc]	11.8[a]
77	10.55[b]	12.77[c]	10.92[b]
82	11.29[a]	13.4[ab]	11.92[a]
88	11.18[a]	13.79[a]	11.69[ab]
SEM[4]	0.13	0.15	0.22
P-Value	0.0012	0.0062	0.0092

[a-c]Least square means within a column with different superscripts differ significantly ($P < 0.05$).

[1]Samples were analyzed for moisture content at 2 different locations (feed mill and farm) to ensure moisture content of feed was kept below the threshold (12%) during storage.

[2]FM = Feed mill

[3]F = farm

[4]SEM= Standard error of the mean for conditioning temperatures.

Table 3. 4 Growth performance of Ross × Ross 708 male broilers fed diets subjected to different conditioning temperatures from 15 to 49 d of age[1]

Conditioning	Body Weight Gain, g		Feed Intake, g		FCR[2], g:g	
Temperatures, °C	Grower	Finisher	Grower	Finisher	Grower	Finisher
71	1008	2347	1525	4168	1.52	1.99
77	1004	2352	1498	4202	1.50	2.01
82	1023	2382	1526	4218	1.51	2.01
88	993	2300	1489	4123	1.53	2.02
SEM[3]	10	41	16	60	0.008	0.023
P-value	0.252	0.565	0.286	0.683	0.067	0.725

[1]Values are least square means of 10 replicate pens with 28 birds at placement. Grower = 15 to 28 d of age; finisher = 29 to 49 d of age.

[2]FCR = Feed conversion ratio was corrected for mortality.

[3]SEM = Standard error of the mean for conditioning temperatures.

Table 3. 5 Processing characteristics of Ross × Ross 708 male broilers fed diets subjected to different conditioning temperatures from 15 to 49 d of age

Conditioning	Carcass		Breast		Tenders		Wings	
Temperatures, °C	Weight[1] (g)	Yield[2] (%)	Weight (g)	Yield (%)	Weight (g)	Yield (%)	Weight (g)	Yield (%)
71	3,007	78.9	889	29.5	161[bc]	5.4	290	9.6
77	3,000	80.2	873	29.1	160[c]	5.4	287	9.6
82	3,068	78.9	904	29.4	168[a]	5.5	293	9.6
88	3,031	78.8	885	29.2	167[ab]	5.5	288	9.5
SEM[3]	29	0.72	12	0.23	2	0.06	3	0.06
P-value	0.353	0.500	0.335	0.565	0.021	0.086	0.497	0.407

[a-c]Least square means within a column with different superscripts differ significantly ($P < 0.05$)
[1]Carcass weight was the average of 10 birds/pen randomly selected at d 49.
[2]Percent of live weight was calculated by part weight/live BW × 100.
[3]SEM = Standard error of the mean for conditioning temperatures.

Table 3. 6 Apparent Ileal Digestibility of nutrients (%) and energy (kcal/kg) determined in broilers fed grower (15–28 d) diets subjected to different conditioning temperatures[1]

Conditioning Temperatures, °C	Apparent Ileal Digestibility (%)		Ileal Digestible Energy[2] (kcal/kg)
	Crude Protein	Crude Fat	
71	76.17[a]	84.42	2,769[a]
77	72.16[b]	86.25	2,725[ab]
82	71.29[b]	84.79	2,679[b]
88	73.38[b]	82.47	2,785[a]
SEM[3]	0.749	1.037	25.712
P-Value	0.0003	0.0998	0.0282

[a-c]Least square means within a column with different superscripts differ significantly ($P < 0.05$)

[1]Values are least square means of duplicates of ileal contents of 4 birds per pen.

[2]Ileal digestible energy, calculated by multiplying the AID of GE× GE of diet.

[3]SEM= Standard error of the mean for conditioning temperatures.

IV. EVALUATION OF PARTICLE SIZE, FEED FORM AND PELLET DIAMETER ON PERFORMANCE, CARCASS CHARACTERISTICS, NUTRIENT DIGESTIBILITY AND GI TRACT DEVELOPMENT OF BROILERS

ABSTRACT

The objective of the study was to elucidate the effect of corn particle size and feed form on broiler performance, processing yield, nutrient digestibility, and gastrointestinal tract (**GIT**) development from 1 to 39 d of age. A total of 1,800 Cobb 500 broilers was randomly assigned to 9 dietary treatments with 8 replicates per treatment and 25 birds/pen. Experimental design consisted of a 3 × 3 factorial arrangement of 3 corn particle sizes (750, 1,150 and 1,550 μm) and 3 feed forms (mash, 3- and 4-mm pellets) provided from 1 to 39 d. Titanium dioxide (TiO_2) was added as an indigestible marker (0.5%) during the finisher phase (27 to 39 d) to determine nutrient digestibility. Feed intake (**FI**) and body weight (**BW**) were determined at 17, 27 and 39 d of age and FCR corrected for mortality. On d 40, 10 birds per pen were processed and on d 41, carcasses were deboned to determine carcass and parts weight and yield. Broilers fed 3- and 4-mm pellets had higher BW, FI and lower FCR ($P<0.05$) than broilers fed mash diets at 39 d of age. Broilers fed diets with 750 µm corn particle size had higher ($P<0.05$) BW than broilers fed diets with 1,550 µm corn particle size at 39 d. Broilers fed diets with 750 µm corn particle size had higher ($P<0.05$) FI than broilers fed diets with corn ground to 1,150 and 1,550 µm. FCR at 39 d of age was unaffected by corn particle size. Relative weights of gizzard, pancreas and small intestine segments were higher ($P<0.05$) in broilers fed mash compared to pelleted diets. Broilers fed diets with 750 µm corn particle size had lower ($P<0.05$) relative gizzard weight than broilers fed diets with corn ground to 1,550 µm. Broilers fed 3 mm pellets had the heaviest ($P<0.05$) carcass and breast weights, followed by 4 mm pellets and lightest weights exhibited by broilers

fed mash diets. Broilers fed diets with 750 µm corn particle size had heavier carcass and breast weights (P<0.05) than broilers fed diets with 1,550 µm, but similar to broilers fed diets with 1,150 µm corn particle size. Digestibility of nutrients was enhanced by pelleting particularly when corn particle size increased. Breast myopathies, such as wooden breast and stringy spongy, were higher (P<0.05) in broilers fed 3 mm pellets compared to mash. Although the incidence of breast myopathies was increased in broilers fed pelleted diets, the results of this study elucidated the beneficial effects of pelleting on broiler performance, carcass characteristics, and nutrient digestibility. Alternatives for feeding pelleted diets that stimulate GI tract development are needed in order to improve feed efficiency.

INTRODUCTION

Manipulation of cereal grains particle size and pellet size of broiler diets have become important in poultry production. Cereal grains are typically ground prior to their incorporation in poultry diets to increase surface area for steam penetration during feed conditioning and particle binding during pelleting as well as to improve the exposure of digesta to digestive enzymes (Reimer, 1992; Behnke, 2001). However, finely ground components in poultry feeds are rapidly dissolved in the crop after consumption and limit gizzard development due to a lack of mechanical stimulation (Engberg et al., 2002; Svihus, 2011). Indeed, whole grains or coarse cereal particles have been previously included in broiler diets to stimulate gizzard development, reverse peristalsis and holding capacity, resulting in reduced passage rate and improved nutrient digestibility (Svihus, 2011).

Pelleted diets have been utilized to reduce feed wastage, mealtime, selective feeding, and nutrient segregation as well as to increase FI, BWG, bird uniformity, resting time, and feed efficiency (Behnke, 1996). Pelleting also appears to influence the gastrointestinal tract development, Nir et al. (1995) reported decrease weight of proventriculus, gizzard and small intestine in birds fed pelleted compared to mash diets. Variations in pellet diameter have also been evaluated to determine the ideal pellet size for optimal growth, feed efficiency and nutrient digestibility and to match the oral cavity of birds (Cerrate et al., 2009; Sundu et al., 2009; Abdollahi et al., 2012; Rubio et al., 2020). However, studies evaluating the effect of pellet diameter on pellet quality and performance of modern broiler lines are scarce.

Therefore, a better understanding of the interactive effects of feed form, corn particle size, and pellet diameter is necessary to optimize growth performance, carcass yield, and nutrient utilization of modern broiler strains. This study was conducted to evaluate the effects of particle size, feed form and pellet diameter on broiler performance, digestive tract development, processing yield and nutrient digestibility from 1 to 39 d of age.

MATERIALS AND METHODS

All procedures involving live birds were approved by Auburn University Institutional Animal Care and Use Committee (PRN 2019-3517).

Birds and Housing

A total of 1,800 d-old male Cobb 500 broilers obtained from a commercial hatchery was weighed and randomly allocated to 72 floor pens in an environmentally controlled house (25 birds/pen; 0.10m^2/bird). Birds and feed were weighed to determine body weight (BW), feed intake (FI) at 17, 27 and 39 d of age and feed conversion ratio (FCR) was corrected for mortality. The research facility was equipped with exhaust fans, forced-air heaters, cooling pads, and electronic controllers to manage temperature and ventilation. Feed and water were offered *ad libitum* with 1 tube feeder and 5 nipple drinkers in each pen. Chicks received 0.7 kg of starter feed from d 1 to 17, 1.45 kg of grower feed from d 17 to 28 and finisher feed thereafter. The lighting program consisted of 23L:1D from d 1 to 7, 21L:3D from d 8 to 21, and 16L:8D from d 22 to 39. Room temperature was set at 32°C from d 1 to 2, 31.3°C from d 3 to 5, 29.4°C from d 6 to 14, 28.3°C from d 15 to 21, 26.7ºC from d 22 to 28, and 23.8ºC from d 29 to 39. Housing conditions and mortality were monitored daily.

Feed Formulation, Manufacture and Experimental Design

Experimental diets were identical in nutrient and ingredient composition in all treatments with the only difference being corn particle size and feed form. Treatments consisted of a 3 × 3 factorial arrangement of 3 corn particle sizes (750, 1,150 and 1,550 µm) and 3 feed forms (mash, 3- and 4-mm pellets) provided from 1 to 39 d. Whole corn was ground with a hammermill (Model 11.5 × 38, Roskamp Champion, Waterloo, IA) equipped with 7.94-mm screen and a variable frequency drive (VFD) on the main drive motor to adjust hammer tip speed and control geometric mean particle size by mass (D_{gw}) to achieve average particle sizes of 750, 1,150, and 1,550 µm . Corn used in the study was ground at the beginning of the experiment to ensure same nutritional composition and particle size during the entire trial. After corn grinding, dry ingredients were blended for 150 s (30 s dry cycle and 120 s wet cycle) in a twin shaft mixer (Model 726, Scott Equipment Co., New Prague, MN) to produce mash diets. Pelleted diets were conditioned at 82°C for 45 seconds and pelleted through either a 3- or 4-mm pellet die (Model 1112-4, California Pellet Mill Co., Crawfordsville, IN). Pellets were then cooled with ambient air using a counter-flow pellet cooler (Model CC0909, California Pellet Mill Co., Crawfordsville, IN). Starter feed for pelleted treatments was crumbled in a crumbler with manual roll adjustment (Model 624SS, California Pellet Mill Co., Crawfordsville, IN). Titanium dioxide (TiO_2) was added as an indigestible marker at 0.5% inclusion to determine nutrient digestibility during the finisher period (27 to 39 d of age).

Measurements

After grinding, corn particle size was determined using a 13-sieve stack with US sieve numbers 6, 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200, 270, and pan. A Ro-Tap shaker (Model RX-30 W.S. Tyler's Ro-Tap®, Mentor, OH) was used to sift 100 ± 5 g samples for 10 min. Geometric mean particle size by mass (D_{gw}) and the geometric standard deviation of particle diameter by mass (S_{gw}) were calculated using the quantity of material retained on each sieve following the ASABE method S319.4 (ASABE Standards, 2009).

Finished feed bags were randomly collected during feed bagging to evaluate the effect of corn particle size and pellet diameter on pellet durability index (PDI), which was determined using the ASABE method S269.5 (ASABE Standards, 2012). Pellets with 3- and 4-mm diameter were sifted using a No. 6 and No. 8 American Society for Testing and Materials sieves, respectively.

Feed and BW were recorded per pen at 17, 27, and 39 d of age. Mortality was removed, weighed, and recorded daily and its weight was used to adjust FCR. On d 39, one bird per pen was selected within +/- 3% of the mean weight. Selected birds were euthanized using CO_2 followed by cervical dislocation, and GI tract organs such as gizzard, proventriculus, pancreas, duodenum, jejunum, and ileum were weighed to determine their relative weight. In addition, the relative length of duodenum, jejunum, and ileum were measured. The length of each intestinal segment was determined with a flexible metric tape on a metal surface table to prevent inadvertent stretching. The length of the duodenum (from the pyloric junction to the distal-most point of insertion of the duodenal mesentery), the length of the jejunum (from the distal-most point of insertion of the duodenal mesentery to the junction with Meckel's diverticulum), and the length of the ileum (from the junction with Meckel's diverticulum to the ileocecal junction) were measured. After separating and freeing each segment from any adherent mesentery, their empty weights were determined.

Furthermore, on d 39, 4 birds per pen were randomly selected and euthanized using CO_2 followed by cervical dislocation. Ileal digesta was collected (2 cm posterior of Meckel's diverticulum to 2 cm anterior of the ileal-cecal junction) by gently squeezing the ileal contents in a manner that provided enough sample (10-12 g after freeze-dried) for digestibility analysis. Ileal digesta samples were frozen, lyophilized, and ground. Experimental diets and ileal digesta were analyzed for crude protein (**CP**), fat, and gross energy (**GE**) content. Crude protein was analyzed by determining the nitrogen content via the Dumas method (method 990.03; AOAC International 2006) using a N analyzer (Rapid N Cube, Elementar Analysensyteme GmbH, Hanau, Germany) with CP being calculated by multiplying percent N by a correction factor (6.25). Gross energy was determined using an adiabatic bomb calorimeter (Parr, 6300, Parr Instruments, Moline, IL) standardized with benzoic acid. Crude fat concentrations were estimated with the AOAC method 2003.06 (AOAC International, 2006) using a fat extractor (Soxtec model number 2043, Foss North America, Inc., Eden Prarie, MN). Titanium dioxide (TiO_2) concentration was determined following the procedures of Short et al. (1996). Apparent ileal digestibility (**AID**) of crude protein, fat, and energy were calculated using the following equation:

$$\text{AID }\%=\{[(\text{Nutrient}/TiO_2)_{\text{diet}} - (\text{Nutrient}/ TiO_2)_{\text{digesta}}] / (\text{Nutrient}/ TiO_2)_{\text{diet}}\} \times 100$$

were ($\text{Nutrient}/TiO_2$) = ratio of CP, fat or GE to TiO_2 in diet or ileal digesta. Energy digestibility (%) values obtained from this equation were multiplied by the GE content of feed to calculate apparent ileal digestible energy **(IDE)** in units of kcal/kg. Titanium dioxide concentration on diet samples ranged from 0.41 to 0.48%.

On d 39, 10 birds per pen were randomly selected, wing banded, and marked with feed-grade dye to evaluate carcass and parts weight and yield. Feed was removed from each pen 10 hours prior to processing, but birds had access to drinking water during the feed removal period. On d 40, selected birds were loaded into coops and transferred to the Auburn University Pilot Processing Plant. Broilers were electrically stunned, exsanguinated, scalded, picked and eviscerated mechanically and placed on ice. After processing, carcasses were chilled in ice water for 4 hours and then excess water was drained for approximately 5 minutes prior to determining chilled carcass weight. Carcass yield was calculated in relation to live BW, whereas parts' yield was calculated as a percentage of chilled carcass weight. On d 41, carcasses were deboned using stationary cones to determine meat yield (breasts, wings, and tenders) and incidence of breast myopathies. Wooden breast (**WB**) was evaluated by hand palpation, scoring the breast from completely normal (score 0), mild (score 1), moderate (score 2) to severe (score 3). Stringy spongy (**SS**) was evaluated by pinching the top surface of the breast fillet and looking for turgor (presence or absence).

Statistical Analyses

Data were analyzed as a 3 × 3 factorial (corn particle size × feed form) using a randomized complete block design. Each of the 9 treatments was represented by 8 replicates. Pen location was the blocking factor. Data were analyzed using the GLM procedure of JMP software (SAS Institute Inc., Cary, NC) with the following mixed-effects model:

$$Y_{ij} = \mu + \rho_i + \tau_j + (\rho\tau)_{ij} + \varepsilon_{ij}$$

were Y_{ij} = observed response of the bird in the pen; μ = is the overall mean; ρ_i is the effect of the ith level of feed form, τ_j is the effect of the jth level of corn particle size, $(\rho\tau)_{ij}$ is the effect of the interaction between the ith level of feed form and the jth level of corn particle size,

εij are identically and independently normally distributed random errors with mean 0 and variance σ^2. The least squared mean values among the 9 treatments were compared using Tukey's HSD procedure with statistical significance considered at $P \leq 0.05$ unless otherwise indicated.

For analyzing the breast myopathies frequency and severity, Statistical analysis was performed using the GLIMMIX procedure of SAS (PC version 9.4, SAS Inst. Inc., Cary, NC). Satterthwaite adjustment was used to correct degrees of freedom with pen serving as the experimental unit. Proportional data were analyzed using the events/trials syntax with a binomial distribution and both continuous and proportional data were analyzed using an R-side covariance structure. Data were analyzed as a two-way ANOVA and least squares means were separated using the PDIFF option for multiple means comparisons and considered significantly different when $P \leq 0.05$.

RESULTS AND DISCUSSION

Feed quality parameters

Geometric mean diameter of ground corn used during experimentation is shown in Figure 4.1. Main effects of pellet diameter and corn particle size and their interactions are presented on Table 4.2. Pellet diameter × corn particle size interactions were observed for pellet durability index (**PDI)** in both grower and finisher diets. Increments in PDI, during the grower phase, were more evident in diets pelleted using a 3 mm die and using a 4 mm die during the finisher phase. Moreover, in both grower and finisher diets, PDI increased ($P<0.05$) when diets were pelleted using a 3 mm die compared to 4 mm. Furthermore, PDI increments ($P<0.05$) were observed as corn particle size increased from 750 to 1,550 µm. According to Abdollahi et al. (2012, 2013a), reductions in pellet diameter enhance frictional forces as mash feed is extruded through the pellet die and a reduced pellet diameter provide more heat transfer and starch gelatinization to the center of the pellet. In previous studies, Stevens (1987) reported a higher degree of starch gelatinization in the outer portion of pellets compared to their center. According to Löwe (2005), a reduced pellet diameter permits higher and more uniform starch gelatinization with lower breaking points inside pellets, which yields higher pellet quality. Similarly, Cerrate et al. (2009) reported higher pellet quality in diets pelleted using a 1.59-mm diameter die hole compared to diets pelleted with a 3.17-mm. Several authors have reported enhanced pellet durability with reduced particle size (Wondra et al., 1995; Chewning et al., 2012; Mohammadi Ghasem Abadi et al., 2019). However, in pellets with coarse corn particle size, these coarse particles can remain on top of the sieve used to screen fines after the tumbling process and be counted as whole pellets even if the correct sieve is used during pellet durability calculations. Rubio et al. (2017) reported linear increments in PDI as corn particle size increased from 629 to 1,779 µm particularly when PDI was analyzed using the Holmen tester and suggested that mesh with diameter of 1.58 mm, could have retained particles >1,558 µm when determining pellet durability.

Broiler performance variables

Effects of feed form and corn particle size on performance variables at 17, 27, and 39 d of age are presented in Table 4.3. Corn particle size × feed form interactions ($P<0.05$) were found in BW at 17 d of age and in FCR at 17 and 27 d of age. In birds fed mash diets, as corn particle size increased from 750 µm to 1,150 µm, there was a decrease in BW at 17 d of age and an increase in FCR at 17 and 27 d of age. However, when diets were fed as 3- and 4-mm pellets, corn particle size did not influence BW and FCR at 17 and 27 days of age. No feed form and corn particle size interaction on BW, FI and FCR was observed at 39 d of age. Similar interactions have been previously reported (Parsons et al., 2006; Amerah et al., 2007; Chewning et al., 2012; Lv et al., 2015; Mohammadi Ghasem Abadi et al., 2019) were growth performance of broilers fed pelleted diets remained unaffected by particle size. Similarly, several authors (Killburn and Edwards, 2001; Parsons et al., 2006; Chewning et al., 2012; Xu et al., 2015b) have reported higher FCR as particle size was increased, particularly in young chicks, which might be due to higher energy expenditure for gizzard contraction as particle size increases. However, Amerah et al. (2007) reported lower FCR when broilers were fed diets with 1,164 µm of wheat particle size compared to broilers fed diets with 839 µm and attributed the improvement in FCR to improved gizzard function and reduced passage rate, which allowed for longer exposure of digesta to digestive enzymes and better peptide digestion. Nevertheless, the influence of particle size is less evident in pelleted diets due to the degree of grinding that occurs in the pellet mill as feed is extruded between rolls and the pellet die. In the current research, interactions observed at 17 and 27 d of age, also suggest that young broilers are not able to efficiently consume and digest diets containing coarse corn particles.

Broilers fed 3- and 4-mm pelleted diets had higher BW and FI and lower FCR in comparison to broilers fed mash diets throughout the experimental period. Several authors have reported greater BW and FI when birds are fed pelleted diets compared to mash (Engberg et al., 2002; Dozier et al., 2010; Hu et al., 2012; Abdollahi et al., 2018; Naderinejad et al., 2016; Rubio et al., 2019). Pelleting reduces feed wastage, energy expenditure during feeding, and contributes to higher feed consumption and nutrient digestibility (Amerah et al., 2007).

Broilers fed diets with 750 µm corn particle size had heavier BW at 39 d of age than birds fed diets with 1,550 µm corn particle size, but similar to birds fed diets with 1,150 µm corn particle size. Furthermore, broilers fed diets with 750 µm corn particle size had higher FI than broilers fed diets with 1,150 and 1,550 µm corn particle size at 39 d of age. According to Parsons et al. (2006) broilers have a preference for coarse particles, however, two-thirds of the treatments used in this trial were fed in a pelleted form, which prevented broilers from choosing feed particles by their size. Since most of the diets were fed in a pelleted form, likely, once feed reached the gizzard, pelleted diets with reduced corn particle size (750 µm) required less gizzard grinding activity and moved faster into the small intestine increasing feed intake. Corn particle size did not influence FCR at 39 d of age. The results of this study also suggest that optimum particle size of corn is influenced by bird age and feed form.

Processing

Data for carcass characteristics are presented in Table 4.4. No significant feed form × corn particle size interactions were observed on carcass and parts' weight and yield; therefore, only main effects will be discussed. Broilers fed with 3 mm pellets had higher ($P<0.05$) carcass weight and yield than broilers fed mash diets, with broilers fed 4 mm pellets as intermediate. Broilers fed 3 mm pellets had the highest ($P<0.05$) breast weight, followed by broilers fed 4 mm pellets, while broilers fed mash diets had lower ($P<0.05$) breast weight compared to the pelleted treatments. Furthermore, broilers fed 3- and 4-mm pelleted diets had higher ($P<0.05$) breast meat yield and tender and wing weights compared with mash diets. However, broilers fed mash diets had higher ($P<0.05$) wing yield than the pelleted treatments. Similarly, Rubio et al. (2019) reported increased carcass, breast and tender weight in broilers fed with 3.3 mm pellets compared to broilers fed mash diets. These results are likely due to greater feed and nutrient intake and higher nutrient digestibility (Amerah et al., 2008) with more energy and amino acids directed to muscle development and meat accretion in broilers fed pelleted diets.

Corn particle size affected ($P<0.05$) all carcass characteristics excepting breast yield and wing weight and yield. Broilers fed diets with corn ground to 750 µm had heavier ($P<0.05$) carcass and breast weights compared with broilers fed diets with corn particle size of 1,550 µm, but similar to broilers fed diets with 1,150 µm. However, broilers fed diets with corn particle size of 1,150 µm had greater (P<0.05) carcass yield than broilers fed diets with corn particle size of 750 µm. Tender weight and yield were greater (P<0.05) in birds fed diets containing corn ground to 750 µm compared to diets containing corn particle sizes of 1,150 and 1,550 µm. In contrast to our results, Lv et al. (2015) reported no effects of feed form and particle size on carcass characteristics. However, Parsons et al. (2006) reported lower breast weight and yield as feed particle size was increased from 950 to 2,242 µm.

Nutrient Digestibility

Significant (P<0.05) feed form × corn particle size interactions were observed for apparent ileal digestibility (AID) of crude protein (CP), fat, and IDE (Table 4.5). Particle size of corn did not influence (P<0.05) AID of CP when diets were fed as mash or 4 mm pellets , however in broilers fed 3 mm pellets AID of CP was increased as corn particle size was increased from 750 to 1,550 µm. In broilers fed mash diets, AID of fat was reduced (P<0.05) as corn particle increased, however it remained unaffected in broilers fed pelleted diets. Ileal digestible energy remained unaffected by corn particle size when broilers were fed mash and 4 mm pelleted diets, however in birds fed 3 mm pellets, IDE was higher (P<0.05) when corn particle size increased from 750 to 1,550 µm. Similarly, Wondra et al. (1995) observed a similar pattern, reduced particle size increased intakes of digestible dry matter and N when diets were fed in a mash form, however reduced particle size decreased intakes of digestible nutrients when diets were fed in pelleted form. Pelleting reduces nutrient segregation after mixing, enhances particle size uniformity within the pellet, allows birds to consume all necessary and formulated nutrients in every bite, and promotes biochemical changes in starch and protein increasing their digestion (Behnke, 1996).

Feed form significantly influenced AID of CP, fat, and IDE (P<0.05). Apparent ileal digestibility of CP, fat, and IDE were increased (P<0.05) in broilers fed 3- and 4-mm pelleted diets compared to broilers fed mash diets. Similarly, Parsons et al. (2006) reported improvements in N and lysine retention when birds were fed hard pellets (0.2% of a commercial binder and manufactured at 5 to 6 ton/h) compared to soft pellets (2.5% of tap water inclusion and manufactured at 5 to 7 ton/h). However, Naderinejad et al. (2016) and Abdollahi et al. (2018) reported that pelleting reduced the coefficient of apparent ileal digestibility (CAID) of N in comparison with mash diets. Increased CP digestibility in pelleted diets could be explained by the degree of protein denaturation involving the breakdown of the three-dimensional structure, changing the bioactivity of the protein during thermal processing (Rakic, 2012), and increasing the breaking of cell walls of the aleurone layer making protein easily accessible to digestive enzymes (Saunders et al., 1969). However, the pelleting process is influenced by several factors such as conditioning temperature and retention time during feed conditioning, die specifications, and fat addition among others; variation in these factors can influence the outcomes as observed in previous studies. In the current study parameters were chosen carefully to simulate current industry conditions used during the pelleting process.

Fat digestibility was enhanced (P<0.05) in broilers fed pelleted diets regardless of corn particle size. Fat digestibility was likely improved by disruption of ingredient cell walls during pelleting causing a greater exposure of cellular content to bile acids and digestive lipases (Abdollahi et al. 2013b; Naderinejad et al., 2016). Similarly, Abdollahi et al. (2013b) reported improved coefficient of apparent ileal digestibility of fat by pelleting compared to mash diets. Bozkurt et al. (2019) reported increased ether extract digestibility in egg-laying pullets fed crumbles compared to mash diets, which they supported by an increment in pancreatic lipase activity. In contrast, Ege et al. (2019) reported no effect in fat digestibility when laying hens were fed crumbles or mash diets. Differences observed between studies can be influenced by bird type, age, nutritional composition of feed, fat/oil quality and source. The results observed in the current research agree with the results reported by other authors who have reported higher apparent digestibility of GE (Wondra et al., 1995) and ME (Killburn and Edwards, 2001) in pelleted diets compared with mash. Disruption of ingredients' cell walls and thermal modification of starch and protein during pelleting likely increases the access to nutrients by digestive enzymes, resulting in increased IDE.

While particle size only affected AID of CP ($P<0.05$). Broilers fed diets with corn ground to 1,150 and 1,550 µm had greater digestibility of CP than broilers fed diets with 750 µm. Several authors have reported increased protein digestibility (Pacheco et al., 2013) (1,290 µm), N retention (Mtei et al., 2019) (912 µm) and CP digestibility (Bozkurt et al., 2019) (1,122 µm) in broilers fed diets with coarse corn compared to birds fed diets with fine corn particles. The increments in digestibility with increased particle size observed in this study can be partly explained by greater ($P<0.05$) relative gizzard weight (Table 4.6). A well-developed gizzard has been associated with increased grinding capacity and reverse peristalsis, which enhances enzymatic digestion efficiency and nutrient digestibility (Duke, 1992; Svihus and Hetland, 2001; Amerah et al., 2007).

Broilers fed diets with corn particle size of 1,550 µm had greater GE digestibility than broilers fed diets with 750 µm, with broilers fed 1,150 µm corn particle size as an intermediate. In contrast, increased GE (Mtei et al., 2019) and starch digestibility (Ruhnke et al., 2015; Cordova-Noboa et al., 2020) with coarse particles has also been reported in both mash and pelleted diets. In broiler diets, coarse particles stimulate gizzard function and its grinding capacity, leading to smaller feed particles entering the small intestine where digestion and absorption occurs. The increments in GE observed by increasing feed particle size are likely due to better gastric activity and reduced passage rate, which likely enhanced enzyme substrate interactions leading to better digestion due to longer feed retention time in the small intestine (Xu et al., 2015a).

Digestive Tract Parameters

Data illustrating gastrointestinal tract (**GIT**) development at 39 d of age are presented in Table 4.6. No significant corn particle size × feed form interactions were found on GIT development; therefore, only main effects will be discussed. Broilers fed mash diets exhibited greater ($P<0.05$) gizzard, pancreas, duodenum, jejunum and ileum relative weight compared to broilers fed pelleted diets. Duodenum relative length was greater ($P<0.05$) in broilers fed mash diets compared to broilers fed 3- and 4-mm pellets. In contrast, Dahlke et al. (2003) reported increased gizzard weights in birds fed pelleted diets. However, previous research has reported increased relative gizzard weight in birds fed mash diets compared to birds fed pellets or crumbles (Lv et al., 2015; Hu et al., 2012; Mohammadi Ghasem Abadi et al., 2019). This outcome is likely due to the lack of gizzard stimulation in birds fed pelleted diets as pellets disintegrate in the crop and pass through the proventriculus and gizzard without additional grinding (Engberg et al., 2002). Additional grinding during pelleting likely reduces the average particle size inside the pellets and limits gizzard development in broilers fed pelleted diets (Zaefarian et al., 2016). Greater relative pancreas weight might indicate increased pancreatic activity (Dozier, 2019). Engberg et al. (2002) reported higher activity of amylase, lipase, chymotrypsin, and trypsin when birds were fed mash diets compared to pelleted diets.

Information regarding the effect of feed form and particle size on the development of duodenum, jejunum, and ileum is scarce. However, in a study by Naderinejad et al. (2016), the relative weight of intestine segments was unaffected by feed form, but morphometry in duodenum and jejunum (villus height and crypt depth) was greater in birds fed pelleted diets than birds fed mash diets. Xu et al. (2015a) suggested that reduced intestinal weight and length may result in improved feed efficiency due to reduced maintenance costs. Similarly, other authors have reported reduced relative length of the intestine in birds fed pelleted diets (Choi et al., 1986; Nir et al., 1994; Amerah et al., 2007; Naderinejad et al., 2016) compared to birds fed mash diets.

Corn particle size influenced gizzard relative weight. Birds fed diets with corn ground to 1,550 µm had greater ($P<0.05$) relative gizzard weight than birds fed diets with corn ground to 750 µm. These results are in agreement with Engberg et al. (2002), Parsons et al. (2006) and Singh et al. (2014) reported greater gizzard relative weight when coarse particles were included in broiler diets. Similarly, Pacheco et al. (2013) reported greater gizzard relative weight in birds fed coarse corn compared to fine corn. These results are mainly attributed to an increased grinding activity of the gizzard when coarse or fibrous particles are included in poultry feeds.

Breast Myopathies

No significant feed form and corn particle size interactions on the frequency of breast myopathies such as wooden breast (**WB)** and stringy spongy (**SS)** were found. Therefore, main effects of feed form are shown in Figures 4.2 and 4.3. Figure 4.2 shows the frequency of presence and absence of SS, broilers fed mash and 4 mm pelleted diets had the lowest ($P<0.05$) presence of SS compared to broilers fed 3 mm pellets. Figure 4.3 shows the incidence and severity of feed form on WB scoring. Broilers fed mash diets had the highest frequency of normal breast (score 0) compared to broilers fed 3-and 4-mm pellets. Mild and moderate scores of WB in broilers remained unaffected by changes in feed form. However, birds fed 3 mm pellets had the highest (P<0.05) frequency of severe WB (score 3), followed by broilers fed 4 mm pellets and lowest (P<0.05) by broilers fed mash diets.

According to Griffin et al. (2018) broilers with high growth rate, feed efficiency and breast muscle yield are more likely to develop breast myopathies and supports our findings, where broilers fed 3 mm pelleted diets had the heaviest breast weights differing from both, broilers fed 4 mm pelleted and mash diets (Table 4). These abnormalities have been associated with rapid growth rate and muscle size affecting structure, metabolism and repair mechanisms in breast muscles (Velleman et al., 2014; Velleman, 2015; Barbut, 2019).

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Table 4. 1 Ingredient and nutrient composition of dietary treatments varying in feed form and particle size fed to Cobb × Cobb 500 male broilers from 1 to 39 d of age.

Ingredients, % "as fed"	Starter	Grower	Finisher
Corn 7.4% CP	56.62	62.59	66.56
Soybean Meal 46.9% CP	37.79	32.08	27.33
Corn Oil	2.05	2.04	3.23
Dicalcium Phosphate	1.19	0.85	0.88
Limestone	0.92	0.80	0.82
Titanium Dioxide	0.00	0.00	0.50
Salt 96%	0.37	0.37	0.38
DL Methionine	0.36	0.33	0.29
L-Lysine HCl	0.25	0.21	0.22
Choline Cl-60 %	0.06	0.06	0.07
L-Threonine 98%	0.16	0.12	0.08
Trace-mineral premix[1]	0.10	0.10	0.10
Vitamin premix[2]	0.10	0.08	0.05
Quantum Phytase[3]	0.01	0.01	0.01
Calculated analysis, % (unless otherwise noted)			
AME_n kcal/kg	2,975	3,065	3,110
Crude Protein	22.16	19.88	17.95
Digestible Lys	1.26	1.10	1.00
Digestible Thr	0.86	0.75	0.65
Digestible TSAA[4]	0.94	0.86	0.78
Calcium	0.90	0.76	0.76
Available Phosphorus	0.45	0.38	0.38

[1]Mineral premix include per kg of diet: Mn (manganese sulfate), 120 mg; Zn (zinc sulfate), 100 mg; Fe (iron sulfate monohydrate), 30 mg; Cu (tri-basic copper chloride), 8 mg; I (ethylenediamine dihydriodide), 1.4 mg; and Se (sodium selenite), 0.3 mg.

[2]Vitamin premix includes per kg of diet: Vitamin A (Vitamin A acetate), 18,7390 IU; Vitamin D (cholecalciferol), 6,614 IU; Vitamin E (DL-alpha tocopherol acetate), 66 IU; menadione (menadione sodium bisulfate complex), 4 mg; Vitamin B12 (cyanocobalamin), 0.03 mg; folacin (folic acid), 2.6 mg: D-pantothenic acid (calcium pantothenate), 31 mg; riboflavin (riboflavin), 22 mg; niacin (niacinamide), 88 mg; thiamin (thiamin mononitrate), 5.5 mg; D-biotin (biotin), 0.18 mg; and pyridoxine (pyridoxine hydrochloride), 7.7 mg.

[3]Quantum® Blue 5G (AB Vista Feed Ingredients, Marlborough, UK) provides per kg of diet: 500 FTU/kg of phytase activity

[4]TSAA = total sulfur amino acids.

Table 4. 2 Effects of pellet diameter and corn particle size on pellet durability index (PDI) of grower and finisher feeds[1]

Pellet Diameter, mm	Particle Size, μm	Grower	Finisher
	750	91.97[b]	86.62[b]
3.0	1,150	92.59[b]	87.99[b]
	1,550	93.81[a]	89.72[a]
	750	89.18[d]	77.94[e]
4.0	1,150	90.81[c]	80.18[d]
	1,550	89.74[d]	84.89[c]
SEM[2]		0.24	0.35
Main Effects			
3.0		92.79[a]	88.11[a]
4.0		89.91[b]	81.00[b]
SEM		0.16	0.25
	750	90.58[b]	82.28[c]
	1,150	91.70[a]	84.08[b]
	1,550	91.78[a]	87.31[a]
SEM		0.20	0.31
---------*P-values*---------			
Pellet Diameter		<0.0001	<0.0001
Particle Size		<0.0001	<0.0001
Pellet Diameter × Particle Size		<0.0001	<0.0001

[a-c]Least square means within a column with different superscripts differ significantly ($P < 0.05$)
[1]Values are least square means of duplicates of 5 feed bags per treatment.
[2]SEM= Standard error of the mean for pellet diameter × corn particle size as well as for main effects.

Table 4. 3 Growth performance of Cobb × Cobb 500 male broilers fed diets varying in feed form and corn particle size from 1 to 39 d of age[1]

Feed Form	Particle Size, µm	Body Weight, g			Feed Intake, g			Feed Conversion Ratio[2], g:g		
		1-17 d	1-27 d	1-39 d	1-17 d	1-27 d	1-39 d	1-17 d	1-27 d	1-39 d
Mash	750	631[b]	1,411	2,829	787	1,963	4,270	1.34[b]	1.47[b]	1.58
	1,150	595[bc]	1,344	2,754	750	1,909	4,184	1.37[ab]	1.51[a]	1.60
	1,550	564[c]	1,290	2,711	732	1,890	4,135	1.42[a]	1.55[a]	1.61
3 mm Pellet	750	795[a]	1,764	3,333	919	2,335	4,817	1.22[c]	1.38[c]	1.52
	1,150	758[a]	1,697	3,226	880	2,238	4,626	1.24[c]	1.39[c]	1.51
	1,550	766[a]	1,712	3,237	910	2,298	4,738	1.26[c]	1.41[c]	1.54
4 mm Pellet	750	749[a]	1,688	3,227	882	2,241	4,677	1.26[c]	1.39[c]	1.53
	1,150	755[a]	1,658	3,224	893	2,248	4,629	1.26[c]	1.42[c]	1.51
	1,550	753[a]	1,683	3,181	885	2,245	4,600	1.26[c]	1.40[c]	1.52
SEM[3]		11.8	25.6	42.6	13.5	31.2	48.0	0.009	0.009	0.013
Main Effects										
Mash		596[b]	1,348[b]	2,765[b]	756[b]	1,921[b]	4,196[b]	1.38[a]	1.51[a]	1.60[a]
3 mm Pellet		773[a]	1,724[a]	3,265[a]	903[a]	2,291[a]	4,727[a]	1.24[b]	1.39[b]	1.52[b]
4 mm Pellet		752[a]	1,676[a]	3,211[a]	886[a]	2,245[a]	4,635[a]	1.26[b]	1.40[b]	1.52[b]
SEM		7.19	14.9	24.2	8.11	18.0	27.7	0.005	0.006	0.007
	750	725[a]	1,621[a]	3,130[a]	862	2,180	4,588[a]	1.27[b]	1.41[b]	1.54
	1,150	703[ab]	1,566[b]	3,068[ab]	841	2,132	4,480[b]	1.29[b]	1.44[a]	1.54
	1,550	694[b]	1,562[b]	3,043[b]	842	2,145	4,491[b]	1.31[a]	1.45[a]	1.56
SEM		7.19	14.9	24.2	8.11	18.0	27.7	0.005	0.006	0.007
---------- *P-values* ----------										
Feed Form		<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Particle Size		0.008	0.0099	0.0437	0.1004	0.1618	0.0135	<.0001	<0.0001	0.1710
Feed Form × Particle Size		0.0409	0.2307	0.7481	0.0898	0.4055	0.4002	0.0118	0.0014	0.3885

[a-c]Least square means within a column with different superscripts differ significantly ($P < 0.05$)
[1]Values are means of 8 replicate pens with 25 birds at placement.
[2]Feed conversion ratio = corrected for mortality.
[3]SEM = Standard error of the mean for feed form × corn particle size as well as for main effects.

Table 4. 4 Processing characteristics of Cobb × Cobb 500 male broilers fed diets varying in feed form and corn particle size from 1 to 39 d of age

Feed Form	Particle Size, µm	Cold Carcass (g)[1]	Cold Carcass %[2]	Breast (g)	Breast %	Tenders (g)	Tenders %	Wings (g)	Wings %
Mash	750	2,222	71.0	579	26.0	123	5.55	227	10.26
	1,150	2,224	73.6	568	25.5	117	5.27	232	10.49
	1,550	2,172	71.9	547	25.1	114	5.25	225	10.39
3 mm Pellet	750	2,617	72.5	696	26.6	140	5.33	262	10.02
	1,150	2,539	74.9	676	26.7	134	5.31	257	10.16
	1,550	2,539	75.0	677	26.6	134	5.28	257	10.11
4 mm Pellet	750	2,522	74.3	667	26.4	136	5.43	258	10.23
	1,150	2,525	74.9	665	26.4	133	5.31	256	10.16
	1,550	2,482	72.1	658	26.5	132	5.35	253	10.22
SEM[3]		22.3	0.83	8.31	0.21	1.67	0.05	2.41	0.06
Main Effects									
Mash		2,206[c]	72.2[b]	564[c]	25.5[b]	118[b]	5.4	228[b]	10.4[a]
3 mm Pellet		2,562[a]	74.2[a]	683[a]	26.6[a]	135[a]	5.3	258[a]	10.1[b]
4 mm Pellet		2,509[b]	73.8[ab]	663[b]	26.4[a]	134[a]	5.4	255[a]	10.2[b]
SEM		12.9	0.48	4.79	0.12	0.96	0.03	1.39	0.03
	750	2,453[a]	72.6[b]	647[a]	26.4	133[a]	5.4[a]	249	10.17
	1,150	2,426[ab]	74.5[a]	636[ab]	26.2	128[b]	5.3[b]	248	10.27
	1,550	2,397[b]	73.0[ab]	627[b]	26.1	126[b]	5.3[b]	245	10.24
SEM		12.9	0.48	4.79	0.12	0.96	0.03	1.39	0.03
---------- *P-values* ----------									
Feed Form		<0.0001	0.0113	<0.0001	<0.0001	<0.0001	0.4297	<0.0001	<0.0001
Particle Size		0.0100	0.0156	0.0135	0.3019	<0.0001	0.0023	0.0932	0.1875
Feed Form × Particle Size		0.2454	0.0693	0.5105	0.2046	0.6318	0.0970	0.2551	0.2599

[a-c]Least square means within a column with different superscripts differ significantly ($P < 0.05$)

[1]Carcass weight was the average of 10 birds/pen randomly selected at d 39.

[2]Percent of live weight was calculated by part weight/live BW × 100.

[3]SEM = Standard error of the mean for feed form × corn particle size as well as for main effects.

Table 4. 5 Apparent Ileal Digestibility of nutrients (%) and energy (kcal/kg) determined in broilers during the finisher phase (28–39 d), fed diets varying in feed form and corn particle size[1]

Feed Form	Particle Size, μm	Apparent Ileal Digestibility, %		Ileal Digestible Energy[2], kcal/kg
		Crude Protein	Crude Fat	
Mash	750	77.90[bcd]	88.16[b]	2958[bc]
	1,150	76.57[cd]	83.31[c]	2841[c]
	1,550	77.61[cd]	81.33[c]	2854[c]
3 mm Pellet	750	76.08[d]	94.48[a]	2991[bc]
	1,150	81.97[ab]	95.38[a]	3066[ab]
	1,550	83.71[a]	96.14[a]	3183[a]
4 mm Pellet	750	80.52[abc]	94.11[a]	3046[ab]
	1,150	82.60[a]	94.28[a]	3087[ab]
	1,550	83.35[a]	95.55[a]	3123[ab]
SEM[3]		0.89	0.90	35.9
Main Effects				
Mash		77.36[b]	84.27[b]	2884[b]
3 mm Pellet		80.59[a]	95.33[a]	3080[a]
4 mm Pellet		82.17[a]	94.65[a]	3086[a]
SEM		0.59	0.61	22.9
	750	78.15[b]	92.31	2999
	1,150	80.39[a]	90.99	2998
	1,550	81.57[a]	90.95	3053
SEM		0.60	0.62	23.4
---*P-values*---				
Feed Form		<0.0001	<0.0001	<0.0001
Particle Size		<0.0001	0.1701	0.1142
Feed Form × Particle Size		0.0003	<0.0001	0.0027

[a-c]Least square means within a column with different superscripts differ significantly ($P < 0.05$)
[1]Values are least square means of duplicates of ileal contents of 4 birds per pen.
[2]Ileal Digestible Energy = calculated by multiplying the AID% of GE × GE of diet.
[3]SEM= Standard error of the mean for feed form × corn particle size as well as for main effects.

Table 4. 6 Effect of feed form and corn particle size on digestive tract development of broilers from 1 to 39 days of age[1]

Feed Form	Particle Size, µm	Relative weight, g/kg of BW						Relative length, cm/kg of BW		
		Gizzard	Proventriculus	Pancreas	Duodenum	Jejunum	Ileum	Duodenum	Jejunum	Ileum
Mash	750	12.9	2.55	1.79	11.3	27.9	27.9	5.7	10.2	8.7
	1,150	14.0	2.84	2.01	11.7	28.8	29.7	6.4	10.8	9.2
	1,550	14.3	2.76	1.99	11.9	29.9	30.4	6.4	11.3	9.8
3 mm Pellet	750	8.13	2.53	1.64	9.4	24.4	24.0	5.6	11.0	8.3
	1,150	10.2	2.44	1.80	9.7	24.9	25.3	5.4	10.2	8.9
	1,550	10.6	2.57	1.69	9.6	24.1	25.1	5.9	10.5	9.1
4 mm Pellet	750	10.3	2.79	1.67	10.1	26.3	25.1	5.7	10.8	8.3
	1,150	10.2	2.50	1.69	9.9	25.1	25.4	5.4	10.4	8.2
	1,550	10.6	2.37	1.65	10.2	25.3	25.4	5.4	9.90	8.6
SEM[2]		0.52	0.08	0.09	0.33	0.75	1.04	0.25	0.44	0.42
Main Effects										
Mash		13.7[a]	2.72	1.93[a]	11.7[a]	28.9[a]	29.4[a]	6.2[a]	10.8	9.2
3 mm Pellet		9.6[b]	2.52	1.71[b]	9.6[b]	24.5[b]	24.8[b]	5.6[b]	10.6	8.8
4 mm Pellet		10.4[b]	2.55	1.67[b]	10.1[b]	25.6[b]	25.3[b]	5.5[b]	10.4	8.4
SEM		0.30	0.04	0.05	0.18	0.44	0.58	0.15	0.26	0.23
	750	10.4[b]	2.62	1.70	10.3	26.2	25.7	5.6	10.7	8.4
	1,150	11.5[ab]	2.59	1.84	10.5	26.3	26.8	5.7	10.5	8.7
	1,550	11.8[a]	2.57	1.78	10.6	26.4	26.9	5.9	10.6	9.1
SEM		0.30	0.04	0.05	0.18	0.44	0.58	0.15	0.26	0.23
---------- *P-values* ----------										
Feed Form		<0.0001	0.0957	0.0024	<0.0001	<0.0001	<0.0001	0.0030	0.5260	0.0597
Particle Size		0.0053	0.8592	0.2372	0.5104	0.8998	0.2430	0.3635	0.8501	0.1135
Feed Form × Particle Size		0.2245	0.0534	0.7661	0.8487	0.2366	0.8739	0.1353	0.1545	0.8158

[a-c]Least square means within a column with different superscripts differ significantly (*$P < 0.05$*)

[1]Values are least square means of 8 birds per treatment (1 bird/pen +/-3% of pen mean weight)

[2]SEM= Standard error of the mean for feed form × corn particle size as well as for main effects.

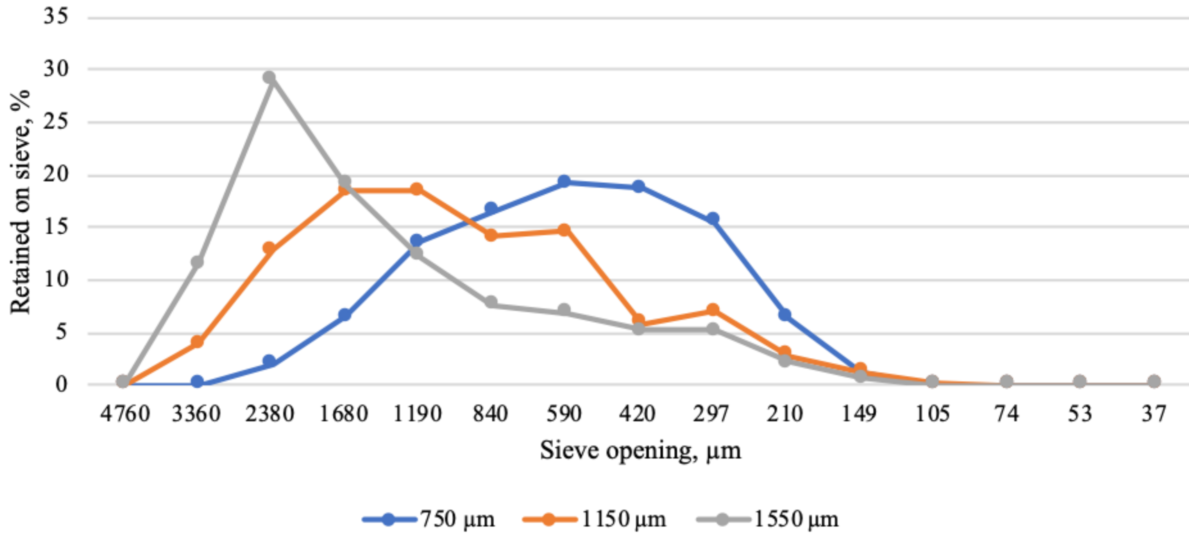

Figure 4. 1 Geometric mean diameter by mass (Dgw) and particle size distribution of corn before mixing. Cobb × Cobb 500 male broilers were fed with diets containing 3 corn particle sizes. Dietary treatments (corn particle size: 750, 1,150 and 1,550 µm) were obtained by grinding whole corn in a hammermill equipped with a 7.94-mm screen and a variable frequency drive (VFD) on the main drive motor to modify hammer tip speed to achieve average particle sizes of 701, 1,160, and 1,611 µm.

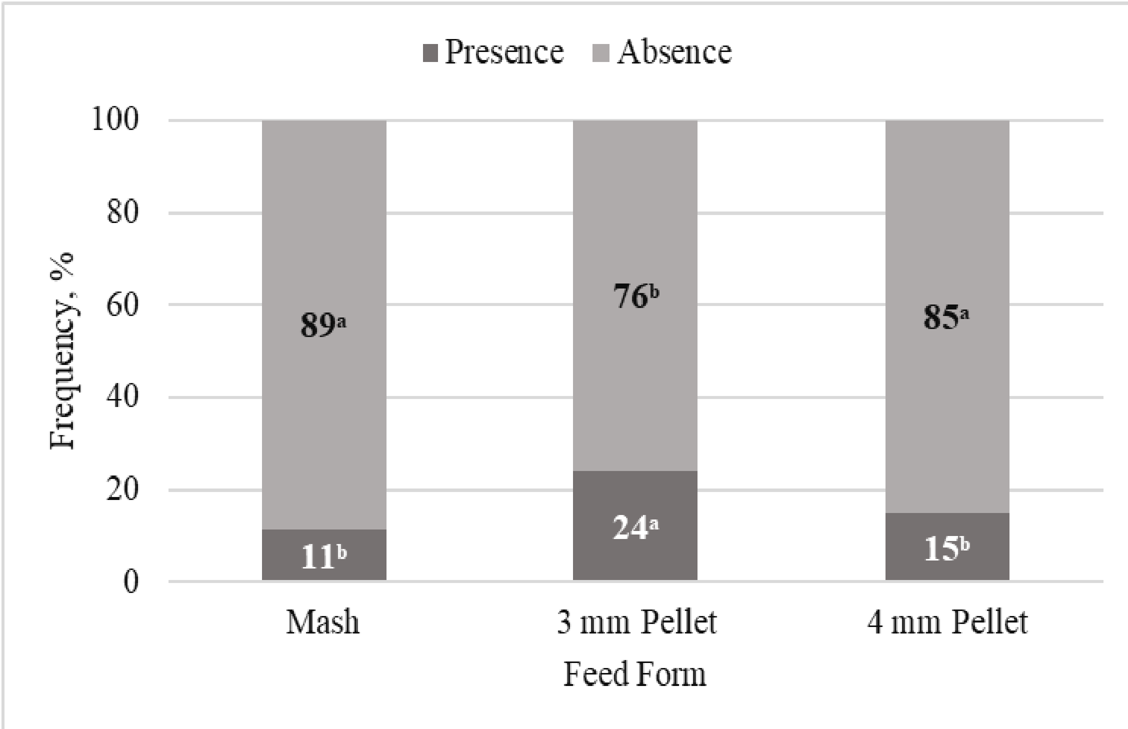

Figure 4. 2 Effect of feed form on frequency (%) of Stringy Spongy (SS) at 39 d of age, n=720.

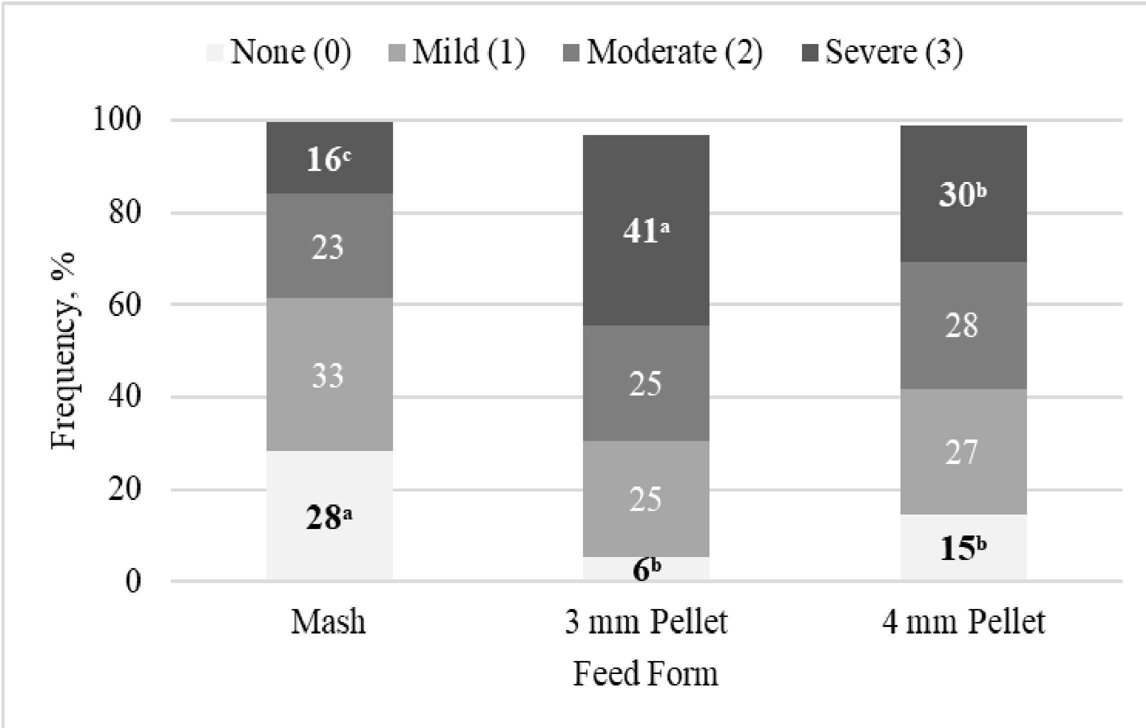

Figure 4. 3 Effect of feed form on frequency and severity (%) of Wooden Breast (WB) at 39 d of age, n=720.

V. CONCLUSIONS

Pelleting has proven to improve broiler performance mainly by increasing feed intake. In addition, other benefits offered by pelleting include increments in the hygienic status of feed, reduced feed wastage, and selective feeding and improvements in bird uniformity (Behnke, 1994). However, during pelleting, conditioning is the most important factor affecting pellet quality. High conditioning temperatures are able to improve feed quality, but nutrient availability can be compromised.

Experiment 1 was conducted to evaluate the effect of conditioning temperature on feed quality, broiler performance, nutrient digestibility and processing yield of broilers. A common starter was fed during the first 14 days. In subsequent phases 4 conditioning temperatures of 71, 77, 82, and 88˚C were considered as treatments and applied to grower and finisher feeds. Digestibility of nutrients was determined for the grower phase. However, feed quality was improved as conditioning temperatures increased. In addition, apparent ileal digestibility of crude protein, and ileal digestible energy were reduced when conditioning temperatures were increased from 71 to 82˚C. In contrast, fat digestibility remained unaffected as conditioning temperatures increased. Similarly, growth performance of broilers and carcass and breast weight and yield were not influenced by conditioning temperatures. Reductions in nutrient digestibility can be explained by changes and modifications during feed processing that negatively affect thermolabile nutrients (amino acids, vitamins) availability. These results suggest that although pellet quality was enhanced and reductions in nutrient digestibility were found, growth performance and processing yield of broilers were unaffected.

Manipulation of particle size and pellet size of broiler diets have become alternatives to improve growth performance in modern broiler production. Whole grains or coarse cereal particles have been previously included in broiler diets to stimulate gizzard development and reverse peristalsis, and holding capacity, thus resulting in reduced passage rate and improved nutrient digestibility (Svihus, 2011). Variations in pellet diameter have also been evaluated to determine the optimum pellet size for optimal growth, feed efficiency and nutrient digestibility and to match the oral cavity of birds (Cerrate et al., 2009; Sundu et al., 2009; Abdollahi et al., 2012; Rubio et al., 2020). However, studies evaluating the effect of pellet diameter on pellet quality and performance of modern broiler lines are scarce. A better understanding of the interactive effects of feed form, corn particle size, and pellet diameter is necessary to optimize growth performance, carcass yield, and nutrient utilization of modern broiler strains.

Experiment 2 was conducted to evaluate the effects of particle size, feed form and pellet diameter on feed quality, broiler performance, digestive tract development, processing yield and nutrient digestibility of broilers. Treatments consisted of a 3 × 3 factorial arrangement of 3 corn particle sizes (750, 1,150 and 1,550 μm) and 3 feed forms (mash, 3- and 4-mm pellets). Digestibility of nutrients was determined for the finisher phase from 28 to 39 d of age. Feed quality was improved as pellet diameter was reduced and as corn particle size increased. Interactions were observed during starter and grower phases. In birds fed mash diets, BW was reduced and FCR increased as corn particle size increased. However, in birds fed 3- and 4-mm pelleted diets, the effect of corn particle size was less evident by the pelleting process due to its grinding effect on coarse particles. These interactions indicate that during pelleting coarse particles or whole grains suffer a reduction in size as these are extruded through the pellet die. Another inference from the interactions observed is that young chicks are not able to efficiently consume diets with coarse particles particularly in mash diets. Pelleting offers the opportunity to increase corn particle size in pelleted diets without negatively affecting performance and reducing the relative weight of the gastrointestinal tract. By pelleting digestibility of nutrients is increased as well as the processing yield of broilers, however, the increased growth rate from broilers fed pelleted diets lead to increased frequency of breast myopathies especially in birds fed 3 mm pellets. Considering that the broiler industry, grinds corn to approximately 900 µm, these results suggest that corn particle size can be increased to 1,550 µm in pelleted diets for grower and finisher diets. Corn can be ground to approx. 1,150 µm and included in mash diets during the starter phase.