Effects of Corn Particle Size and Feed Form on Growth Performance and Carcass Characteristics of Broilers

by

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ABSTRACT

Previous research has shown that manipulation of corn particle size and feed forms have an impact on broiler growth performance. The poultry industry grinds corn to approximately 800 µm before its incorporation into broiler diets. However, coarse particles (>1,000 µm) have been reported to stimulate gizzard development in broilers and reduce electrical energy consumption during grinding. Three trials were conducted to determine the effects of feeding broilers with different corn particle size during the starter (1 to 14 d), grower (14 to 28 d), and finisher (28 to 42 d) periods in order to determine the optimum corn particle size in each phase. Each trial evaluated the effects of 4 corn particle sizes. In trial 1 corn was ground to 674, 741, 805, and 912 µm, in trial 2 corn was ground to 629, 763, 814, and 1,779 µm and in trial 3 corn was ground to 615, 863, 1,644, and 2,613 µm. In trials 1 and 2, the particle size of corn did not influence body weight (**BW**), feed intake (**FI**) and feed conversion ratio (**FCR**). In trial 3, the particle size of corn particle did not influence BW and feed intake of broilers. However, FCR improved on birds fed diets with corn particles ground to 863 µm at 42 d of age compared with those fed diets with corn particles of 1,644 µm and 2,613 µm. These data indicated that coarser particles can be fed during the production periods of broilers without a negative effect on growth parameters although particles >1,600 µm may compromise FCR at 42 d.

Currently, the majority of broiler producers are feeding crumbles during the starter period (1 to 14 d) and 4.4 mm pellets in subsequent phases. However, one processing alternative to improve broiler productive parameters could be feeding 3.3 mm micro pellets during the starter period. Two trials were conducted to evaluate the effects of feeding 3.3 mm micro pellets on broiler performance and carcass characteristics. In the first trial 5 treatments were evaluated during the starter period and consisted of a combination of 3 dietary feed forms: 1) mash from 1 to 14 d, 2) crumbles from 1 to 14 d, 3) 3.3 mm micro pellets 1 to 4 d and then crumbles to 14 d, 4) 3.3 mm micro pellets 1 to 7 d and then crumbles to 14 d, and 5) 3.3 mm micro pellets from 1 to 14 d. Common grower and finisher diets were offered in a 4.4 mm pelleted form from 15 to 35 d of age. The second trial consisted of a 3 x 2 factorial arrangement with 3 feed forms (mash, crumbles + 4.4 mm pellets, and 3.3 mm micro pellets) and 2 amino acid (**AA**) densities (88 and 96% AA of Aviagen Recommendations). In trial 1, birds fed mash diets during the starter period (1 to 14 d) had the lowest BW and feed intake at 35 d compared to birds fed either crumbles or 3.3 mm micro pellets. However, no differences in FCR were observed at 35 d. The usage of 3.3 mm micro pellets during the starter improved breast meat weight at 35 d of age. In trial 2, birds fed 4.4 mm pellet and 3.3 mm micro pellets had higher BW, FI, carcass and breast meat weight and better FCR than birds fed mash diets at 42 d of age. In addition, birds fed diets with 96% of dietary AA had higher BW, carcass yield, carcass weight, and breast meat weight and better FCR than birds fed diets with 88% of dietary AA. These data demonstrated that broilers can be fed 3.3 mm micro pellets during the starter period and/or during a 6 wk production period of broilers.

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I. INTRODUCTION

Feed represents between 60 to 70% of total broiler production costs (Jahan et al., 2006). Therefore, manipulation of feed form and particle size could be an alternative to improve growth performance of meat-type poultry and compensate high feed costs within the manufacturing process at commercial feed mills. Cereal grains must be ground before their incorporation into broiler diets to increase surface area allowing an interaction of digesta with digestive enzymes (Amerah et al., 2007). However, grinding represents the second largest energy cost during feed manufacturing of pelleted feeds (Reece et al., 1985). Previous research has reported that grinding corn to a coarser particle size reduces electrical energy consumption during grinding (Reece et al., 1986; Xu et al., 2015, 2017). However, the optimum particle size of cereal grains used in poultry diets may vary with the productive period of the animal (Ferket and Gernat, 2006; Amerah et al., 2007). Depending on the dimensions of their beak, particle preference for birds in the first week of age may be different than those in the grower and finisher phases (Schiffman, 1968; Portella et al., 1988). Therefore, it is important to determine the optimum particle size of corn-based diets in each productive period to improve broiler growth performance and reduce feed manufacturing costs.

Commercial feed mills are also using various feed forms in broiler feeds such as mash, crumbles or pellets, which are known to influence growth performance in fast-growing chickens (Jahan et al., 2006). Previous studies have reported improved body weight gain (**BWG**) and feed intake on broilers fed crumbled and pelleted diets in comparison to mash diets as they improve palatability, reduces selective feeding, destruction of pathogenic organisms, and less energy expended for prehension (Behnke, 2001; Svihus et al., 2004, Frikha et al., 2009; Abdollahi et al., 2011). Recently, researchers have hypothesized that feeding ~ 2.0 mm micro pellets instead of crumbles during the starter period may improve BW and feed intake in subsequent phases as young broilers are influenced by the physical structure of the diet (Michard and Rouxel, 2015; Xu et al., 2015). Therefore, it is important to evaluate the effects of micro pellets on growth performance of broilers in the grower and finisher periods.

The research presented herein consisted of 2 experiments. Experiment 1 (3 trials) was conducted to evaluate the effects of corn particle size on growth performance of broilers in the starter, grower and finisher periods. This was accomplished by sequentially grinding corn to different coarseness (trial 1: 674, 741, 805, and 912 μm, trial 2: 629, 763, 814, and 1,779 μm and trial 3: 615, 863, 1,644, and 2,613 μm) at the feed mill. Experiment 2 (2 trials) was conducted to investigate the effects of feed form (trial 1: mash, crumbles and 3.3 mm micro pellets from 1 to14 d, 3.3 mm micro pellets 1 to 4 d and then crumbles, and 3.3 mm micro pellets 1 to 7 d and then crumbles, and trial 2: mash at 88% and 96% amino acid (**AA**) density from 1 to 42 d, crumbles from 1 to 14 d + 4.4 mm pellets at 88% and 96% AA density from 14 to 42 d, and 3.3 mm micro pellets at 88% and 96% AA density from 1 to 42 d of age) on broiler productive and processing performance.

II. LITERATURE REVIEW

IMPORTANCE OF CORN PARTICLE SIZE IN THE BROILER FEED INDUSTRY

Feed represents between 60 and 70% of the total broiler production costs (Jahan et al., 2006). Therefore, feeding programs for meat-type poultry are designed to meet their nutrient requirements in each of their productive periods at the lowest possible cost (Dozier et al., 2006). In the U. S., corn is the main energy source in poultry diets, contributing to approximately 65% of the metabolisable energy (Naderinejad et al., 2016). Corn is usually ground before its incorporation into broiler diets (Reece et al., 1986b; Kilburn and Edwards, 2001; Parsons et al., 2006). However, grinding represents the 2nd largest energy cost after pelleting, (Reece et al., 1985). Moreover, grinding costs are influenced by particle size specifications of the ground material (Svihus et al., 2004; Amerah et al., 2007). Previous research evaluating the influence of cereal grain particle size in poultry diets have produced inconsistent results in relation to feed passage rate, nutrient utilization, pellet quality and growth performance (Reece at al., 1985; Reece et al 1986 a,b; Nir et al., 1994 a,b; Hetland et al., 2002; Svihus et al., 2004; Peron et al., 2005; Parsons et al., 2006; Amerah et al., 2007; Dozier et al., 2010; Jacobs et al., 2010; Pacheco et al., 2013; Xu et al., 2015). These studies suggest that the particle size of corn used in broiler diets has an impact on growth responses and economical revenues in the modern commercial broiler industry.

Particle size analysis

The first methodology to describe particle size was approved in 1940 by the American Society of Agricultural Engineers (ASAE); this methodology characterized the particle size of feed ingredients into 8 broad size categories (Behnke, 1983). However, Pfost and Headly (1976) developed a more precise method to calculate particle size using log distribution techniques, statistics, and sieve size. The use of statistics and sieving techniques allowed the ASAE to develop a standard method to measure particle size termed "Methods of Determining and Expressing Fineness of Feed Materials by Sieving" (ASAE Standard S319). The feed industry has used this method to determine the average particle size of ground cereal grains, ingredients, and finished feeds for the last 50 years. The most significant change to the standard methodology is the ANSI/ASAE S319.4 (American Society of Agricultural and Biological Engineers [**ASABE**], 2008), in which shaking time was increased from 10 to 15 min as well as the addition of sieve agitators and dispersion agents to facilitate the sifting of ingredients with high fat content (Kalivoda et al., 2017). Sieving agents are used to decrease the agglomeration of particles and sieve agitators assist particles to move across the sieves (Stark and Chewning, 2012).

Particle size is determined by using a sample with 100 g of ground cereal grains, ingredients or finished feed that is placed on top of a sieve stack in which the sieves are "stacked" according to their mesh size, with the largest mesh size placed on top of the stack. The sieve stack is placed in a shaker, which has a unique circular motion that continuously reorients particles into the mesh and a vertical tapping action that assists in passing particles from top to bottom as they are agitated for either 10 or 15 min until they reach a sieve with a mesh too small to pass through. The amount of material retained on each sieve is weighed and used to calculate the geometric mean particle size (D_{gw}), which is measured in millimeter (**mm**) or microns (**µm**) and the geometric standard deviation (S_{gw}). According to Nir et al. (1995), a smaller D_{gw} represents a higher uniformity. However, variations in equipment, number of sieves, usage of sieve agitators and sieving agents, and sieving time can cause variations in the results obtained during particle size analysis (Fahrenholz et al., 2010). Other variations in the results obtained during particle size analysis include: incorrect sampling, inadequate separation during sifting, moisture, errors in calculations, missing or disarrangement of sieves, and grain quality (Heiman, 2005). Therefore, the particle size of ground cereal grains, ingredients, and finished feeds should be reported based on the ASAE standards, which provides a more accurate description among studies and interpretation of results (Kalivoda et al., 2017).

EFFECTS OF GRINDING EQUIPMENT ON PARTICLE SIZE CHARACTERISTICS

Particle size reduction of cereal grains is obtained through a process called grinding and it is the 2nd stage in feed manufacturing prior blending the rest of the ingredients in the diet (Behnke, 1983). Previous research has reported that the particle size of ground grains may affect nutrient digestibility, feed conversion ratio (**FCR**), mixing characteristics, and pelleting (Reece et al., 1985; Reece et al., 1986 a,b; Nir et al., 1995). Therefore, particle size manipulation of feed ingredients is attractive as it offers the possibility of reducing manufacturing costs within the grinding process and/or increasing nutrient digestibility of the diet (Amerah et al., 2007). The most common equipment for particle size reduction are the hammermill and the roller mill (Nir et al., 1995). Hammermills consist of a rotor(s) plate fixed to a main shaft, grinding occurs as fast-moving hammers shatter slow moving material (Martin, 1985) (Figure 2.1). Particle size in the hammermill is determined by tip speed, hammer and screen design as well as the usage of air assists systems (Fang et al., 1997). Tip speed is described as the product of the diameter (measured from hammer tip to hammer tip) and revolutions per minute (**rpm**) of the motor. Generally, tip speeds higher than 18,000 ft/min produce fine particles while tip speed lower than 13,000 ft/min generate coarser particles (Heiman, 2005). Moreover, the amount of open area in screens is known to influence particle size and grinding efficiency as it is related to horsepower (Fang et al., 1997). Fang et al. (1997) reported that the screen size is directly proportional to the geometric mean particle size of ground particles; screen openings of 1.59 mm and 4.76 mm generate average particle sizes of around 700 and 1,000 µm, respectively. In general, screens with small holes (< 1.58 mm) and high tip speed produce particles lower than 500 µm. However, larger screen sizes and low tip speed (< 13,000 ft/min) require less energy and offer the opportunity for energy savings during grinding (Hamilton and Proudfoot, 1995). Poultry producers use screen sizes between 4.0 mm and 6.35 mm to grind cereal grains as they produce particles of approximately 800 µm, which have given good results in grinding capacity and pellet quality (Reece et al., 1986a; Wondra et al., 1995; Svihus et al., 2004). Hammermills are the most common grinding equipment in the feed milling industry in the U.S. as they have low initial investment, minimal maintenance, grind fibrous materials, and are easy to operate (Reece et al., 1985). However, hammermills have higher energy consumption, produce a less uniform particle size, can generate dust and noise pollution, and generate more heat compared with roller mills (Deaton et al., 1989).

Roller mills are generally used in flour milling. Roller mills use compression to reduce the particle size of grains and they must have a robust frame to support the grinding forces and the weight of the rolls (Schönert, 1988) (Figure 2.2). Roller mills consist of a single, double or triple pair of rolls that are open to a certain gap between each other and are set to have a speed differential to regulate particle size (Heiman, 2005). Larger gap between rolls results in coarse particles while a smaller gap produces fine particles (Schönert, 1988). Roller mills produce less noise, dust and heat increase, which results in less moisture losses and less shrinkage and are more energy efficient than hammermills. However, roller mills require higher initial investment, are more difficult to operate as they require roll adjustments in a regular basis, and do not grind fibrous materials efficiently (Deaton et al., 1989; Fang et al., 1997). Hamilton and Proudfoot (1995) hypothesized that the heat produced by the grinding action of hammermills can influence nutrient bioavailability of cereal grains compared with the roller mills. In terms of particle size distribution, the hammermill produces a particle size more variable than the roller mill (Nir et al., 1995).

The particle size characteristics of the ground ingredients play an important role on broiler growth performance (Amerah et al., 2007). Reece et al. (1986b) reported that broilers fed diets containing corn ground with a hammermill equipped with screen sizes of 3.18 mm (679 μm) and 9.53 mm (1,289 μm) improved body weight gain (**BWG**) and FCR compared to a 6.35 mm (987 μm) screen at 42 d of age. However, a subsequent study reported no differences in growth performance on birds fed diets containing corn ground through 3.18 mm (680 μm), 6.35 mm (990 μm) and 9.53 mm (1,290 μm) screens at 49 d of age (Deaton et al., 1995). Hamilton and Proudfoot (1995) reported that broilers fed diets with corn ground with a roller mill (3.2 mm roller gap) and approximately 2,830 μm in particle size had higher BW compared with broilers that received diets with corn ground with a hammermill (3.2 mm screen size) and approximately 710 μm in particle size at 42 d of age. Dozier et al. (2006) reported that adding 35% of rolled corn with a particle size of 1,500 μm after pelleting did not influence growth rate of broilers at 41 d of age. Conflicting results among studies between the 2 grinding equipment may depend on the target particle size used, grain's physical characteristics, and equipment performance (Reece et al., 1985; Hamilton and Proudfoot, 1995; Fang et al., 1997).

Energy consumption during the grinding process

Physical characteristics and moisture content of cereal grains influence the energy required during the grinding process (Martin, 1985). In general, roller mills are more energy efficient than hammermills (Amerah et al., 2007). Reece et al. (1985) reported that roller mills typically use 14.5% less energy than hammermills, but hammermills have higher grinding capacity. In addition, hammermills require larger motors, air assist system, and more sophisticated noise reduction devices than roller mills (Fang et al., 1997). Because most commercial feed mills use hammermills as their primary grinding device, using screens with larger diameter holes can be an alternative to reduce energy expenditure in the hammermill (Reece et al., 1986a). In addition, countries in Europe, Australia and Canada are using whole grains (wheat, sorghum, barley and oats) in broiler diets to reduce grinding costs and improve the performance of broilers (Jacobs et al., 2010). Wondra et al. (1995) reported that grinding corn to 400 μm (8.1 kWh/ton) required 3 times more energy than grinding it to 1,000 μm (2.7 kWh/ton) and calculated an added cost of $0.32/ton. Even when using roller mills, grinding costs increase as the particle size of cereal grains decrease. For example, grinding costs of a roller mill increased from \$0.10 to \$0.28/ton when the particle size was reduced from 1,200 to 600 µm (Heiman, 2005). Dozier et al. (2006) reported that adding 28% of rolled corn after pelleting decreased energy cost from \$0.88/ton (control) to \$0.74/ton when using a hammermill and to \$0.56/ton when using a roller mill. Based on previous research, increasing the particle size of cereal grains could be a strategy to reduce energy consumption in the grinding process regardless of the grinding device.

Pellet quality

Beacause more than 80% of non-ruminant feed in the U. S. is fed in a pelleted form, is important to maintain good pellet quality until consumption by the birds (Behnke, 2001; Parsons et al., 2006). Coarse particles do not absorb steam effectively during the feed conditioning process particularly when the retention time is less than 20 seconds and coarse particles will be a source of weak spots in pellets (Svihus et al., 2004). On the contrary, fine particle size have a higher surface area, which allows increased moisture and steam penetration during the conditioning process and improves the binding of the ingredients during pelleting (Behnke, 2001). Wondra et al. (1995) reported an improvement from 78.8% to 86.4% in pellet quality when the particle size of corn was reduced from 1,000 to 400 µm. However, Stevens (1987) reported that reducing the particle size of corn from 1,023 to 551 µm and of wheat from 802 to 365 µm did not influence pellet quality. In agreement, other studies have reported no differences in pellet quality in diets with a particle size between 600 and 1,700 µm of corn and wheat-based diets (Reece et al., 1986a; Svihus et al., 2004; Peron et al., 2005).

EFFECTS OF PARTICLE SIZE ON BROILER GROWTH PERFORMANCE

Birds have mechanoreceptors in the beak that allow them to recognize feed particles by its texture (Gentle, 1975). Additionally, birds select their feed based on size and shape, which dictate intake patterns during feed consumption, particularly in mash diets (Gentile, 1985). Schiffman (1968) reported that poultry have a preference for coarse particles. However, fine particles have higher surface area, which increases exposure of digesta with digestive enzymes allowing for better liberation and absorption of nutrients during feed digestion (Lott at al., 1992). In agreement, Pacheco et al. (2013) reported that broilers fed diets with a corn particle size of 1,330 µm had lower feed intake, lower BW, and higher FCR at 19 d of age compared with birds fed diets with a corn particle size of 520 µm. Douglas et al. (1990) reported that broilers fed diets with a corn particle size of 1,470 µm decreased BWG approximately 33 g compared with broilers fed diets with a corn particle size of 947 µm at 21 d of age. In older broilers, Reece et al. (1986b) reported that broilers fed diets with a corn particle size of 679 µm had higher BWG, FI, and improved FCR compared with birds fed diets with a corn particle size of 987 µm at 42 d of age. However, birds fed diets with a corn particle size of 1,289 µm had no differences in growth performance compared with birds fed diets with a corn particle size of 679 µm at 42 d of age. Chewning et al. (2012) reported that broilers fed diets with a corn particle size of 300 µm had higher BW compared with birds fed diets with a corn particle size of 600 µm at 21 d of age but there were no differences at 35 and 44 d of age. Previous research has reported that broilers can be fed diets with a particle size > 1,000 µm without negative effects on broiler growth performance during a 6 wk production period (Reece et al., 1986 a,b; Deaton et al., 1995; Hamilton and Proudfoot 1995; Engberg et al., 2002; Parsons et al., 2006). However, conflicting results among studies suggest that the productive phase of broilers has an impact on particle size requirements thereby affecting growth performance.

Gizzard and gastrointestinal development of broilers

Factors such as genetic strain, environmental temperature (Denbow, 2000), age (Shires et al., 1987), dietary fat concentration (Sell et al., 1983), and non-starch polysaccharides (Almirall and Esteve-Garcia, 1994) influence the passage rate of digesta within segments of the gastrointestinal tract of birds. Birds have smaller intestinal volume than mammals, which is advantageous as the energetic costs of flying increases with the load carried (Caviedes-Vidal et al., 2007). Therefore, birds evolved to have a grinding organ or "the gizzard", which helps to reduce the particle size of the ingredients, increase the mixing of the digesta with digestive enzymes, increase reverse peristalsis, and maintain feed in the intestine for a longer time (Duke, 1992) (Figure 2.3). Researchers have reported that the mechanical pressure exerted by the gizzard during grinding may exceed 585 kg/cm^2 and that the digesta passing from the gizzard into the small intestine is smaller than 40 μm regardless of the original particle size of feed (Cabrera, 1994; Hetland et al., 2002). Therefore, the addition of coarse particles in broiler diets is an alternative to stimulate gizzard function and gut motility in order to improve nutrient digestibility (Nir et al., 1994a). Peron et al. (2005) reported that the inclusion of wheat with a particle size of 955 μm in broiler diets increased gizzard weight compared to diets with a wheat particle size of 380 μm at 24 d of age. Nir et al. (1994b) reported that broilers fed diets with a corn particle size of 1,132 and 2,028 μm had 26 and 41% higher gizzard weight compared to chicks fed diets with a particle size of 627 µm at 21 d of age. Pacheco et al. (2013) reported that broilers fed diets with a corn particle size of 1,330 µm had higher gizzard weight compared with birds fed diets with a corn particle size of 520 µm at 21 d of age. In contrast, Svihus et al. (2004) reported no differences in gizzard weight on broilers fed diets with a wheat particle size of 600 or 1,700 µm at 30 d of age. In addition, incorporation of larger particles has been hypothesized to increase nutrient digestibility and decreasing microbial contamination either by increasing the number of beneficial bacteria or reducing pathogenic bacteria (Gabriel et al., 2003). Coarse particles increase the gastric reverse peristalsis between the gizzard and proventriculus, increasing the secretion of hydrochloric acid by the proventriculus and reducing the pH of the gizzard, which may inactivate pathogenic bacteria such as *Salmonella* and *Clostridium perfringens* before entering the small intestine (Engberg et al., 2002; Bjerrum et al., 2005).

Nutrient digestibility

Coarse ground cereal grains have been reported to increase reverse peristalsis and absorption of nutrients in the upper part of the intestine, improving nutrient digestibility and growth performance in poultry (Duke, 1992; Cabrera, 1994; Hamilton and Proudfoot, 1995; Jacobs et al., 2010). The responses to coarse or fine particles appear to be dependent on the characteristics of the GIT of the animals consuming the feed. Wondra et al. (1995) reported increased apparent digestibilities of dry matter (**DM**) and nitrogen (**N**) in pigs when the corn particle size of the diet decreased corn particle size from 1,000 to 400 µm. Rojas and Stein (2015) reported that standardized ileal digestibility of essential amino acids (**AA**) and crude protein (**CP**) were not influenced in pigs fed diets with 4 corn particle sizes: 865, 677, 485, and 339 µm. In comparison to poultry, pigs do not have a grinding organ "the gizzard" but have a longer GIT and benefit from fine particles with a greater surface area (Nir et al., 1993; Wondra et al., 1995). Svihus et al. (2004) reported no differences in apparent metabolisable energy (**AME_n**) on birds fed diets with a wheat particle size of 1,700 µm compared to 600 µm at 24 d of age. In contrast, Peron et al. (2005) reported that broilers fed diets with a wheat particle size of 380 µm had higher AME_n compared to those fed 955 µm at 21 d of age. Jacobs et al. (2010) reported that feeding broilers diets with a corn particle size of 557, 858, 1,210, and 1,387 µm did not influence ME_n and AA digestibility at 21 d of age. The reverse peristalsis triggered by feeding coarse cereal grains or coarse protein meals can also increase the digestibility of other nutrients. Killburn and Edwards (2001) reported that coarse corn particles improved calcium and phytate phosphorus utilization. In addition, Kilburn and Edwards (2004) reported that bone ash and plasma phosphorus concentrations improved when broilers received a diet containing coarse SBM with an average particle size of 1,239 µm compared to SBM with an average particle size of 891 µm at 16 d of age. Kasim and Edwards (2000) gradually increased corn particle size (484, 573, and 894 µm) and reported a linear relationship between corn particle size and calcium and phosphorus absorption without a negative effect in growth performance at 16 d of age. The beneficial results of coarse particles in nutrient digestibility may be attributed to a longer retention time in the GI tract allowing more time for nutrient digestion and absorption (Amerah et al., 2007a). Parsons et al. (2006) reported that a more balanced amount of nutrients can be obtained by grinding corn between 1,042 and 1,109 µm.

EFFECTS OF FEED FORM AND AMINO ACID DENSITY ON GROWTH PERFORMANCE OF BROILERS

Broilers can receive their feed in the form of mash, pellets, or crumbles (Figure 2.4). Previous research has reported the beneficial effects of feeding crumble-pelleted diets over mash diets on broiler growth performance (Pesti et al., 1983; Reece et al., 1985; McKinney and Teeter, 2004; Brickett et al., 2007; Amerah et al., 2008; Chewning et al., 2012; Xu et al., 2015). In order to facilitate particle prehension and due to the dimensions of their beak, newly hatched chicks receive their feed in a crumbled form during the starter period (Portella et al., 1988). A micro pellet with a diameter of around 2 mm has been fed during the starter period to improve early growth and subsequent performance (Quentin et al., 2004). Michard and Rouxel (2015) reported that newly hatched chicks have a preference for feed particles between 1.5 mm and 2.0 mm in diameter. In addition, they reported increased BWG and feed intake on breeders fed 2.0 mm micro pellets during the first week of age compared to breeders fed crumbled diets. However, Cerrate et al. (2009) reported no differences in growth performance of broilers fed crumbles, 1.59 mm, and 3.17 mm pellets at 13 d of age. Quentin et al. (2004) reported that broilers fed 2.5 mm and 4.0 mm pellets had greater BWG, feed intake and lower FCR compared with birds fed mash diets from 15 to 35 d of age.

The ideal protein concept is a more accurate delivery of AA to meet animal requirements for protein accretion and maintenance and it is expressed as the ideal percentage of all the other indispensable AA in comparison to lysine; however, it may be affected by dietary and environmental factors, energy level, and genetics (Baker and Han, 1994; Wijtten et al., 2004). Previous research has reported improved growth performance and meat accretion on broilers fed higher AA densities during their production periods (Kidd et al., 1998; Kidd et al., 2004; Greenwood et al., 2005; Lemme et al., 2006; Dozier et al., 2008). Pesti et al. (1983) indicated that manipulation of nutrient density and feed form are necessary to evaluate responses on growth performance of broilers. Greenwood et al. (2005) reported that feeding lysine levels of 0.85% did not improved BWG in mash diets but maximum weight gain was obtained when birds received pelleted diets at 1.05% of digestible lysine. However, researchers also reported that birds fed 0.75% lysine in mash form converted lysine more efficient to weight gain compared to birds fed pelleted diets but FCR did not significantly differ beyond 0.75% in all dietary treatments. In pelleted diets, growth performance parameters improve due to increased feed consumption and better protein conversion on broilers fed high levels of dietary AA; however, this combination increases diet costs (Greenwood et al., 2005; Dozier et al., 2008). The positive responses of crumbled and pelleted diets, have led the majority of poultry integrators to provide diets in a crumbled or pelleted form (Nir et al., 1995; Nir and Ptichi, 2001; Cerrate et al., 2009; Michard and Rouxel, 2015). Dozier et al. (2008) reported that 70% of feed consumption occurs between 5 and 9 weeks of age. Therefore, substantial concentrations of protein and AA in an early stage leads to muscle cell development, enhanced growth performance, and meat yield (Fisher and Ashley, 1967; Kidd et al., 2004).

KNOWLEDGE GAPS IN THE LITERATURE

Based on previous research, feeding broilers diets with coarse (> 1,000 μm) corn particle size have the potential to stimulate gizzard development and improve nutrient digestibility compared with fine particles. However, the poultry industry is using the same particle size of ground cereal grains regardless of the productive period. Hence, rather than grinding corn to the same particle size for the entire production period, an optimum corn particle size should be determined in the starter, grower, and finisher periods of broilers. Published literature has not determined an optimum corn particle size for each of the growing periods of broilers, which has been reported to influence the mechanical action of the gizzard, nutrient digestibility, and growth performance.

Previous research has often focused on the effects of micro pellets compared with crumbles during the starter period of broilers. However, it is necessary to evaluate the effects of micro pellets on growth performance in the grower and finisher periods of broilers. Research evaluating AA-dose responses and feed form has been conducted primarily in mash, crumbles and pellets while investigations of AA densities and micro pellets are sparse. Previous research evaluating the effects of micro pellets in growth performance of broilers has not determined AA density responses in the starter, grower, and finisher periods. In order to address these knowledge gaps in the literature, 2 experiments were conducted to evaluate growth performance and carcass characteristics of broilers fed diets with different corn particle sizes and different feed forms. The first experiment evaluated the effects of 4 corn particle size on broiler growth performance during the starter (1 to 14 d), grower (14 to 28 d), and finisher (28 to 42 d) periods. The second experiment was conducted to evaluate the effects of mash, crumbles, 4.4 mm pellets and 3.3 mm micro pellets, and 2 AA densities (88% and 96% of Aviagen recommendations) on growth performance and carcass characteristics of broilers in the starter, grower, and finisher periods.

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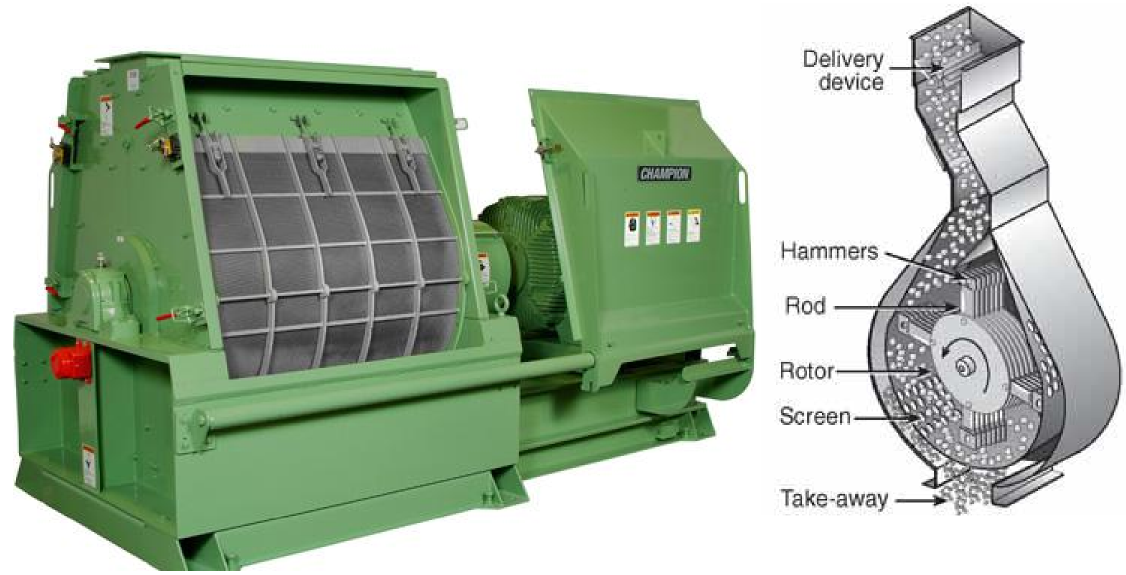

Figure 2.1 Illustration of a hammermill (Heiman, 2005).

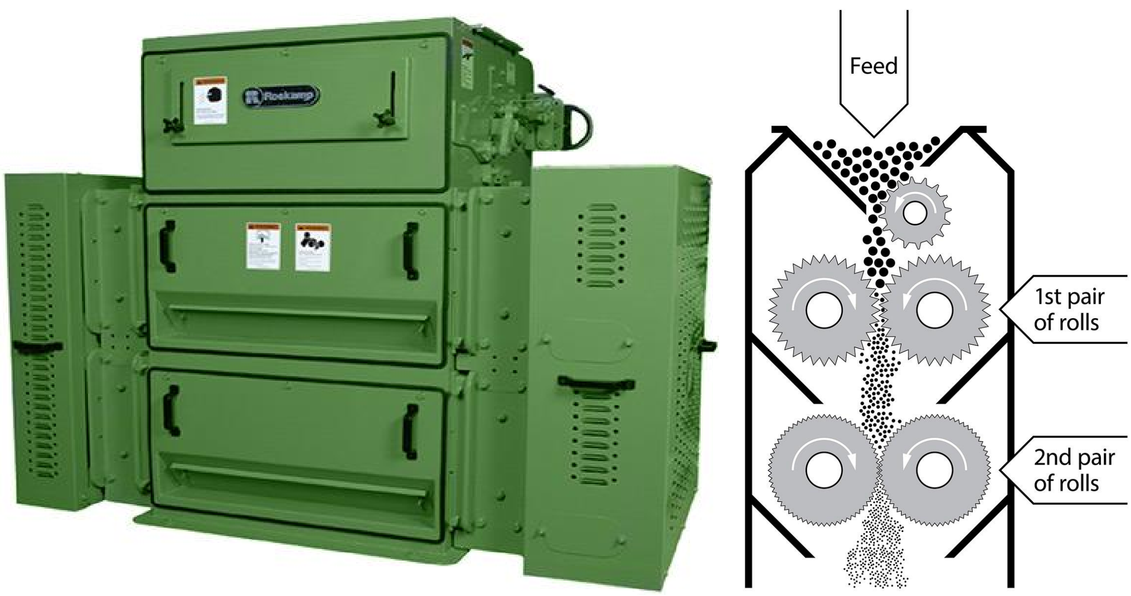

Figure 2.2 Illustration of a roller mill (Heiman, 2005).

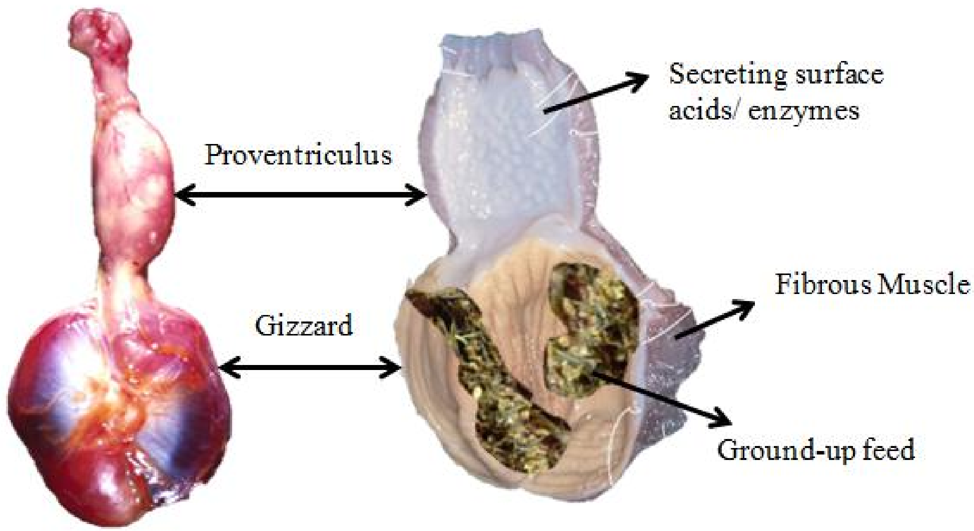

Figure 2.3 Illustration of the proventriculus and gizzard of chickens (Adapted from Buckles et al., 2012).

Figure 2.4 Illustration of different physical feed forms fed by the broiler feed industry.

III. EFFECTS OF CORN PARTICLE SIZE DURING THE STARTER, GROWER, AND FINISHER PHASES ON GROWTH PERFORMANCE OF BROILERS

ABSTRACT

A considerable segment of the poultry industry is grinding corn between 650 and 900 µm throughout the production period of broilers. However, previous research suggests that optimum corn particle size is dependent on bird's beak size and feeding phase. In addition, feeding a coarser particle size (>1,000 µm) could be an alternative to reduce grinding costs. An experiment (3 trials) was conducted to determine the effects of feeding Ross × Ross 708 male broilers different corn particle size during the starter, grower, and finisher phases on growth performance. In trial 1, 4 dietary treatments were fed during the starter period from 1 to 14 d of age consisting of corn particle sizes: 674, 741, 805, and 912 µm. In trial 2, a common starter diet was fed from 1 to 14 d of age and dietary treatments consisted of 4 corn particle sizes: 629, 763, 814, and 1,779 µm fed during the grower period from 14 to 28 d of age. In trial 3, Common grower and finisher diets were offered from 1 to 14 d and 14 to 28 d of age, respectively and the 4 dietary treatments consisted of 4 corn particle sizes: 615, 863, 1,644, and 2,613 µm from 28 to 42 d of age. There were no statistical differences between the treatments on body weight gain (**BWG**), feed intake (**FI**) and feed conversion ratio (**FCR**) during the starter and grower periods in the first and second trial ($P > 0.05$). In trial 3, cumulative BW ($P > 0.05$) and feed intake ($P > 0.05$) were similar among the dietary treatments. However, feed intake increased approximately 200 g when birds were fed diets with a corn particle

size of 1,644 µm compared with those fed diets with a corn particle size of 615 µm from 28 to 42 d of age ($P < 0.05$). Feed conversion ($P < 0.05$) improved on birds fed diets with a corn particle size of 615 and 863 µm compared to diets with a corn particle size >1,600 µm at 42 d of age. These data indicated that diets with a corn particle size of 900 and 1,779 µm did not influence growth performance during the starter and grower periods, respectively. However, a corn particle size >2,000 µm can negatively influence feed intake and FCR during the finisher period from 28 to 42 d of age.

INTRODUCTION

Particle size reduction is a common practice during feed manufacturing as it increases surface area of ground cereal grains, allows for greater interactions between digesta and digestive enzymes, improves pellet quality and mixing uniformity, and reduces segregation after mixing (Douglas et al., 1990; Nir et al., 1995). Nevertheless, grinding represents the 2nd largest energy expenditure after pelleting (Reece et al., 1985). However, grinding cereal grains to a particle size > 1,000 could be an alternative to decrease high energy consumption thereby reduce feed manufacturing costs (Reece et al., 1986b; Wondra et al., 1995). In addition, cereal grains with a particle size > 900 µm have been reported to stimulate gizzard function, enhance reverse peristalsis and feed retention time in the gastrointestinal tract (**GIT**), enhancing nutrient digestibility and feed conversion of broilers (Svihus et al., 2004; Peron et al., 2005; Pacheco et al., 2013). In corn-based broiler diets, it has been hypothesized that the optimum particle size should be between 600 and 900 µm (Amerah et al., 2007). However, previous research has reported that there is a preference for coarser particles as the bird ages and this behavior is more pronounced in the 2nd and 3rd week of age (Schiffman, 1968; Nir et al., 1990; Nir et al., 1994a). A considerable amount of research has evaluated the effects of corn particle size on broiler growth performance, but differences in the experimental period used for the particle size ranges have produced inconsistent results among studies (Douglas et al., 1990; Nir et al., 1994b; Svihus et al., 2004; Peron et al., 2005; Parsons et al., 2006; Jacobs et al., 2010; Benedetti et al., 2011; Pacheco et al., 2013; Lv et al., 2015). Therefore, an experiment was conducted to evaluate the effects of corn particle size in specific growth periods of broilers: from 1 to 14 d, 14 to 28 d, and 28 to 42 d of age.

MATERIAL AND METHODS

All procedures involving live birds were approved by Auburn University Institutional Animal Care and Use Committee (PRN 2016-2944).

Husbandry Practices

Ross × Ross 708 (Aviagen, Huntsville, AL) (1,200- trial 1 and 2; 1,000- trial 3) 1-d-old male broiler chicks were weighed and randomly distributed among 40 floor pens (30 birds/pen; 0.10 m^2/bird) in a solid-sided house with a negative-pressure ventilation system. The facility was equipped with exhaust fans, forced-air heaters, cooling pads, and electronic controllers to adjust temperature and ventilation. Each pen was 150 cm in width, 200 cm in length, and 60 cm in height and was equipped with 5 nipple drinkers and 1 tube feeder. Feed and water were offered *ad libitum* throughout the experimental periods. Chicks received 0.7 kg of starter, 1.8 kg of grower, and approximately 2.8 kg of finisher feed. Photoperiod was set at, 23L:1D from 1 to 7 d, 21L:3D from 8 to 20 d and 16L:8D from 21 to 42 d. The room temperature was 35°C at placement, 31.3°C from 2 to 5 d, 29.4°C from 6 to 14 d, and 28.3°C from 15 to 23 d, 26.7ºC from 24 to 28 d and 23.8ºC from 29 to 42 d.

Feed Formulation, Manufacture, and Experimental Design

Broiler diets were formulated to meet or exceed the NRC suggested minimum nutrient requirements of broilers (NRC, 1994) (Table 2.1). Dietary treatments were formulated with corn and soybean meal (**SBM**) as the primary ingredients. Each pen was randomly assigned to 1 of 4 dietary treatments in trial 1 (674 ± 1.86, 741 ± 2.10, 805 ± 2.32, or 912 ± 2.17 µm), trial 2 (629 ± 2.42, 763 ± 2.52, 814 ± 2.66, or 1,779 ± 2.63 µm), and trial 3 (615 ± 1.89, 863 ± 1.96, 1,644 ± 1.89, or 2,613 ± 1.83 µm) with a total of 10 replicates per treatment. In trial 2, a common starter diet with a corn particle size of 554 µm was fed until 14 d of age. In trial 3, common starter and grower diets with a corn particle size of 650 µm were fed until 28 d of age. All starter feeds were crumbled in a crumbler with manual roll adjustment (Model 624SS, California Pellet Mill Co., Crawfordsville, IN). To create the experimental treatments, whole corn was ground with a hammermill (Model 11.5 × 38, Roskamp Champion, Waterloo, IA) equipped with 3.18-mm, 4.74-mm, 6.35-mm, and 7.94-mm screens to achieve an average particle size of 674, 741, 805, and 912 µm, respectively. In trial 2, a common starter diet was offered in a crumbled form from 1 to 14 d of age. At 14 d, 4 dietary treatments varying in particle size of corn were provided in a pelleted form until 28 d of age. The 4 dietary treatments were obtained by grinding whole corn in a hammermill equipped with 4.74-mm, 6.35-mm, and 7.94-mm screens to obtain an average particle size of 629, 763, and 814 µm, respectively. A 2-pair roller mill (Model DP900-12, Roskamp Champion, Waterloo, IA) was used to achieve a coarser corn particle size with an average particle size of 1,779 µm. In trial 3, common starter and grower diets were fed as crumbles from 1 to 14 d and pellets from 14 to 28 d of age. At 28 d, feeders were emptied to remove the grower feed and 4 dietary treatments varying in particle size of corn were provided in a pelleted form from 28 to 42 d of age. Dietary treatments were obtained by grinding whole corn in a 2-pair roller mill to obtain an average particle size of 615, 863, 1,644 and 2,163 µm. In all 3 trials, dry ingredients were blended in a twin shaft mixer (Model 726, Scott Equipment Co., New Prague, MN) to produce the mash diets, which were conditioned at 82°C for 45 s and pelleted through a 4.4 mm by 35 mm pellet die using a pellet mill (Model 1112-4, California Pellet Mill Co., Crawfordsville, IN). Pellets were cooled with ambient air using a counter-flow pellet cooler (Model CC0909, California Pellet Mill Co., Crawfordsville, IN).

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 determined using the quantity of material retained on each sieve following the shaking according to the ASABE method S319.4 (ASAE Standards, 2008). In trial 2, pellet durability index (**PDI**) was determined by the ASABE method S269.5 (ASAE Standards, 2012). Due to the use of a 5/32 × 1.25 in. die, pellets were sifted in a No. 6 American Society for Testing and Materials (ASTM) screen. Five hundred grams of sifted pellets were placed in a dust-tight enclosure and tumbled for 10 min at 50 rpm. The dimensions of the enclosure were 5 × 12 × 12 in., with a 2 × 9 in. plate affixed diagonally along 1 of the 12 × 12 in. sides. The tumbled samples were then sifted again (No. 6 ASTM) and weighed. Pellet durability index was calculated by dividing the weight of pellets after tumbling by the weight of pellets before tumbling, then multiplying by 100.

Broilers and feed were weighed at the beginning and at the end of each experimental period (1, 14, 28 and 42 d of age) to determine body weight gain (**BWG**), feed intake (**FI**), and feed conversion ratio (**FCR**). Birds were observed twice daily, mortalities were removed and their BW was included in the FCR calculation.

Statistical Analyses

In each experiment, a randomized complete block design was employed with pen location as the 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 (SAS Institute, 2010) software with the following model:

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

Where Y_{ij} = observed response of the birds in the pen; μ = is the overall mean; T_i = fixed effect of corn particle size treatment; and ε_{ij} = residual error when the pen was regarded as an experimental unit, ε_{ij} $N(0, \sigma^2_\varepsilon)$. The mean values among 4 corn particle size treatments were compared using the Tukey's honestly significant different procedure with the significant level at $P \leq 0.05$. Linear and quadratic effects were not considered during data analysis as dietary treatments were not equally spaced.

RESULTS AND DISCUSSIONS

Trial 1: 1 to 14 d of age

The geometric mean diameter of the ground corn used during the starter period is shown in Figure 3.1. Particle size of the ground corn did not influence BWG, feed intake, FCR, and the incidence of mortality from 1 to 14 d of age ($P > 0.05$) (Table 3.2). Xu et al.

(2015) reported similar effects on broilers fed crumbled diets with different inclusion levels of coarse corn without a negative effect in growth performance during the starter period from 1 to 14 d of age. Jacobs et al. (2010) reported no differences in BWG on birds fed diets with a corn particle size of 557, 858, 1,210 or 1,387 µm at 7 d of age. However, Pacheco et al. (2013) reported that broilers fed mash diets with a corn particle size of 1,330 µm had lower BW and feed intake and higher FCR compared with birds fed diets with a corn particle size of 520 µm from 7 to 19 d of age. Nir et al. (1994b) reported that birds fed diets with a corn particle size of 897 µm had greater BWG and lower FCR compared with birds fed diets with a particle size of 2,010 µm from 1 to 7 d of age.

In the case of other cereal grains, Peron et al. (2005) reported that broilers fed diets with a wheat particle size of 380 and 955 µm resulted in no differences in BWG, feed intake, and FCR from 7 to 15 d of age. In addition, Douglas et al. (1990) reported that birds fed diets containing coarse particles of either corn or sorghum (1,470 to 1,800 µm) had lower BWG and higher FCR than birds fed diets with fine particles (833 to 947 µm) from 1 to 21 d of age. However, Nir et al. (1994a) reported that broilers fed corn, wheat, and sorghum diets with a particle size between 970 and 1,270 µm had the highest BW and feed intake compared with birds fed diets with a particle size of ~ 600 µm at 21 d of age. In the present study, feeding broilers diets containing a corn particle size of 912 µm allows optimum growth performance from 1 to 14 d of age.

Trial 2: 14 to 28 d of age

The geometric mean diameter of the ground corn used during the grower period is shown in Figure 3.2. A roller mill was used to grind the coarsest particle size (1,779 ± 2.63 µm) in order to evaluate the effects of a corn particle size larger than 1,500 µm on broiler growth performance during the grower period. Corn particle size did not influence BWG, feed intake, FCR, and the incidence of mortality from 14 to 28 d of age ($P > 0.05$) (Table 3.3). In agreement, Svihus et al. (2004) reported no statistical differences in BWG, feed intake, and FCR when birds were fed wheat-based diets with a particle size of 600 and 1,700 µm from 11 to 30 d of age. Singh et al. (2014) reported that diets with a corn particle size of 578, 726, 877, 987, and 1,172 µm had no impact on BWG, feed intake, and FCR from 11 to 35 d of age. Similarly, Lv et al. (2015) reported no differences in BW and feed intake on birds fed diets with a corn particle size of 573, 865, and 1,027 µm from 22 to 32 d of age. Parsons et al. (2006) reported that broilers fed diets with a corn particle size of 781, 950, 1,042, and 1,109 µm, had lower feed intake and higher FCR compared with birds fed diets with a particle size of 2,242 µm during the grower period from 21 to 42 d of age. Although not measured in this trial, the authors concluded that a corn particle size up to 1,109 µm may improve nutrient profile thereby improve nutrient digestion compared with a particle size of 2,242 µm which was speculated to have higher maintenance requirements.

Despite corn particle size did not influence growth performance during the grower period; this effect could be attributable to a further particle size reduction within the manufacturing process. It has been reported that coarse particle may go through a "grinding" process between the die and the rolls during the pelleting process which evens out the differences (Svihus et al., 2004). In the present study, corn particle size did not compromise growth performance which indicates that a particle size > 1,000 µm is suitable for broilers during the grower period. It has been reported that this effect may be attributable to an increase in particle preference for coarser particles in older birds (Schiffman, 1968; Portella et al., 1988).

It has been reported that particle size influences 20% of pellet quality (Behnke, 2001). Wondra et al. (1995) reported that pellet durability improved from 78.8% to 86.4% as the particle size of corn was reduced from 1,000 to 400 µm. In addition, Chewning et al. (2012) reported that diets with a corn particle size of 300 µm improved pellet quality from 82% to 85% compared to diets with a particle size of 600 µm. According to Svihus et al. (2004), coarse particles generate fracture points within the pellet, which increases pellet breakage and the percentage of fines. Therefore, it was expected that diets with a corn particle size of 1,779 µm would decrease pellet quality; however, this negative effect did not happen. In the present study, pellet quality values, as determined by the PDI test for the grower diets were 83, 85, 85, and 84%. The particle size of corn (629, 763, 814, and 1,779 µm) did not influence pellet quality ($P > 0.05$) (Figure 3.4). In agreement, Reece et al. (1986a) reported that diets with a corn particle size of 910 and 1,024 µm did not influence pellet quality and concluded that in pelleted diets, particles agglomerate inside the pellet regardless of their original particle size. In wheat-based diets, Svihus et al. (2004) reported no statistical differences in pellet quality when the particle size of wheat was 600, 930, and 1,700 µm. Similarly, Peron et al. (2005) reported that diets with a wheat particle size of 380 and 955 µm did not influence pellet quality. In addition, Stevens (1987) reported that reducing the particle size of corn from 1,023 to 551 µm and of wheat from 802 to 365 µm did not influence pellet quality.

Trial 3: 28 to 42 d of age

The geometric mean diameter by mass and the geometric standard deviation of particle diameter by mass of the ground corn used during the finisher period is shown in Figure 3.3. Corn particle size did not influence BWG, FCR, and the incidence of mortality from 28 to 42 d of age ($P > 0.05$) (Table 3.4). Feed intake increased approximately 180 g on birds fed diets with a corn particle size of 1,644 µm compared with birds fed diets with a particle size of 615 µm from 28 to 42 d of age ($P < 0.05$) (Table 3.4). However, FCR was higher on birds fed diets with a corn particle size of 1,644 µm compared with birds that received diets with a corn particle size of 615 at 42 d of age ($P < 0.05$). Previous research has reported the effects of feeding diets with a corn particle size > 1,000 µm on BWG and FCR in more mature birds during the finisher period. Lv et al. (2015) reported that diets with a corn particle size of 573, 1,110, and 1,183 µm did not influence broiler BWG and FCR from 33 to 40 d of age. In agreement, Reece et al. (1986b) reported no differences in BWG and FCR when broilers were fed diets with a corn particle size of 910 and 1,024 µm from 21 to 46 d of age. Kheravii et al. (2017) reported similar BWG in broilers fed diets with a corn particle size of 1,113 and 3,576 µm from 24 to 35 d of age. Zang et al. (2009) reported that the mixture of corn and SBM ground to a particle size of approximately 600 and 700 µm before blending with the rest of the ingredients had no differences on BWG and FCR of broilers from 22 to 42 d of age. The lack of differences in their study may be attributable to the small difference (100 µm) in particle size used for the corn and SBM.

Previous research has reported that diets with a corn particle size > 1,000 increases feed intake during the finisher period (Parsons et al., 2006; Amerah et al., 2007; Chewning et al., 2012; Xu et al., 2015, 2017). According to Hetland et al. (2002), increased feed intake may be attributable to feed spillage when feeding coarse particles in the diet. However, excessive feed wastage was not observed in the current study. In contrast, Lv et al. (2015) reported no differences in feed intake on broilers fed diets with a corn particle size of 573, 1,110, and 1,183 µm from 33 to 40 d of age. Foltz et al. (2017) reported no differences in feed intake when broilers were fed diets with a corn particle size of 539 and 1,117 µm from 23 to 40 d of age.

The results of the present study agreed with those reported by Reece et al. (1985) in which diets with a corn particle size of 1,343 µm increased FCR of broilers compared to diets with a particle size of 814 µm at 47 d of age. Chewning et al. (2012) reported that broilers fed diets with a corn particle size of 600 µm had higher FCR compared to diets with a corn particle size of 300 µm at 44 d of age. However, a recent study reported that broilers fed diets with a corn particle size of 3,576 µm had lower FCR compared with birds fed diets with a corn particle size of 1,113 µm at 35 d of age (Kheravii et al., 2017). The authors concluded that the beneficial effects of coarse corn particle size are more pronounced in later stages of the grow-out period due to a higher secretion of digestive enzymes. In the present study, the differences attributable to particle size in FCR may have been due in part to the corn particle size of the diets fed in the common starter and grower diets (650 µm) from 1 to 28 d of age. It has been reported that feeding coarse particles in the first week of age is important to stimulate the mechanical action of the gizzard when coarser particles are fed in subsequent phases (Nir et al., 1994b; Hetland et al., 2002; Taylor and Jones, 2004; Amerah et al., 2007; Xu et al., 2017). These data demonstrated that diets with a corn particle size of 1,644 µm can be fed during the to promote feed intake without compromising BWG and FCR during the finisher period from 28 to 42 d of age.

Based on the results of this experiment, birds can be fed diets containing a corn particle size of 912 and 1,779 µm during the starter (1 to 14 d) and grower (14 to 28 d) periods respectively, without a negative effect in growth performance of broilers. In the finisher period (28 to 42 d), diets with a corn particle size of 1,644 µm may increase feed intake compared to diets with a particle size of 615 µm. Further investigation on the relationship of a corn particle size > 900 µm in the starter and grower periods and > 1,000 in the finisher period with broiler growth performance, gizzard development, and pellet quality are required if the corn particle size is to be optimized during the finisher period.

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Table 3.1 Ingredient and nutrient composition of dietary treatments fed to Ross × Ross 708 male broilers from 1 to 42 d of age, trial 1, 2, 3

Ingredient, % "as-fed"	Starter	Grower	Finisher
Corn	51.96	58.83	61.88
Soybean Meal, 46% Crude Protein	35.97	27.56	23.14
Distillers dried grains with solubles (DDGS)	5.00	7.00	9.00
Poultry Oil	3.40	3.33	3.45
Dicalcium phosphate, 18% P	1.27	0.97	0.48
Calcium carbonate	1.24	1.16	1.02
Sodium chloride	0.37	0.37	0.28
D-L Methionine	0.28	0.25	0.20
L-Lysine	0.12	0.17	0.18
Trace mineral premix[1]	0.10	0.10	0.10
Vitamin premix[2]	0.10	0.10	0.10
Choline Chloride	0.08	0.07	0.08
L-Threonine	0.04	0.06	0.06
Copper chloride[3]	0.02	0.02	0.02
Quantum phytase[4]	0.01	0.01	0.01
	100.00	100.00	100.00
Calculated analysis, % (unless otherwise noted)			
AME_n, kcal/kg	3,025	3,117	3,175
Crude Protein	23.24	20.45	19.01
Digestible Lys	1.18	1.02	0.95
Digestible Thr	0.77	0.68	0.63
Digestible Trp	0.23	0.19	0.18
Digestible TSAA[5]	0.91	0.78	0.72
Calcium	1.00	0.88	0.76
Available phosphorus	0.48	0.42	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]Intellibond ® C (Micronutrients, Indianapolis, IN).
[4]Quantum® Blue 5G (AB Vista Feed Ingredients, Marlborough, UK) provides per kg of diet: 500 FTU/kg of phytase activity.
[5]TSAA = Total sulfur amino acids

Table 3.2. Growth performance of Ross × Ross 708 male broilers fed diets with varying corn particle size from 1 to 14 d of age, trial 1[1]

Item	BW gain, g/bird[2]	Feed intake, g/bird	FCR, g:g[3]	Mortality, %[6]
Particle size of corn, μm[4]				
1) 674	467	541	1.183	1.0
2) 741	464	540	1.179	1.3
3) 805	459	540	1.161	1.0
4) 912	459	537	1.160	1.0
SEM[5]	13	15	0.038	0.005
P-value	0.349	0.924	0.420	0.968

[1]Values are least-square means of 10 replicate pens, with each pen having 30 chicks at placement (40 g/bird).
[2]BW= Body Weight
[3]Feed conversion ratio was corrected for mortality.
[4]Treatments consisted of diets of 674, 741, 805, and 912 μm corn particle size.
[5]SEM= Standard error of the means for corn particle size effect (n=10).
[6]Mortality values were arcsin transformed.

Table 3.3 Growth performance of Ross × Ross 708 male broilers fed diets with varying corn particle size from 14 to 28 d of age, trial 2[1]

Item	BW gain, g/bird[2]	Feed intake, g/bird	FCR, g:g[3]	Mortality, %[6]
Particle size of corn, µm[4]				
1) 629	1,174	1,654	1.380	0.0
2) 763	1,170	1,650	1.386	0.0
3) 814	1,173	1,668	1.399	0.3
4) 1,779	1,172	1,668	1.394	0.6
SEM[5]	31	13	0.007	0.002
P-value	0.989	0.679	0.471	0.282

[1]Values are least-square means of 10 replicate pens, with each pen having 30 chicks at placement (40 g/bird).
[2]BW= Body Weight
[3]Feed conversion ratio was corrected for mortality.
[4]A common diet was offered during the starter period with a particle size of 554 µm and dietary treatments consisted of 629, 763, 814 and 1779 µm corn particle size.
[5]SEM= Standard error of the means for corn particle size effect (n=10).
[6]Mortality values were arcsin transformed.

Table 3.4 Growth performance of Ross × Ross 708 male broilers fed diets with varying corn particle size from 28 to 42 d of age, trial 3[1]

Item	BW, g/bird[2]	Feed intake, g/bird	FCR, g:g[3]	BW gain, g/bird	Feed intake, g/bird	FCR, g:g	Mortality, %[6]
	42 d			28 to 42 d			
Particle size of corn, µm[4]							
1) 615	3,231	4,977	1.575[bc]	1,636	2,742[b]	1.677	0.8
2) 863	3,294	5,065	1.574[c]	1,678	2,828[ab]	1.689	0.8
3) 1,644	3,333	5,208	1.599[a]	1,712	2,920[a]	1.706	0.4
4) 2,613	3,250	5,070	1.597[ab]	1,650	2,802[ab]	1.704	0.4
SEM[5]	38	59	0.007	26	37	0.009	0.005
P-value	0.239	0.066	0.041	0.185	0.014	0.137	0.867

[a-b]Means within a column with different superscripts differ significantly ($P < 0.05$).

[1]Values are least-square means of 10 replicate pens, with each pen having 25 chicks at placement (40 g/bird).

[2]BW= Body Weight

[3]Feed conversion ratio was corrected for mortality.

[4]A common diet was offered during the starter and grower period with a particle size of 650 µm and dietary treatments consisted of 615, 863, 1,644 and 2,613 µm corn particle size.

[5]SEM= Standard error of the means for corn particle size effect (n=10).

[6]Mortality values were arcsin transformed.

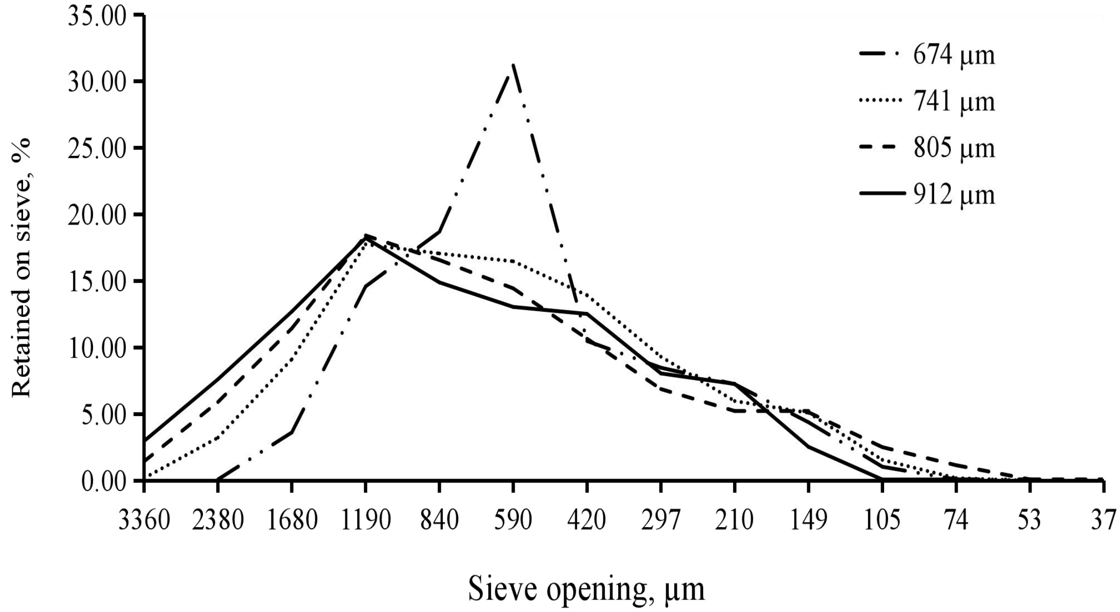

Figure 3.1 In trial 1, the geometric mean diameter by mass (D_{gw}) and particle size distribution of corn prior mixing was determined in the starter period from 1 to 14 d of age (A). Ross × Ross 708 male broilers were fed 4 corn particle sizes over the starter period from 1 to 14 d of age (n=10). Dietary treatments were obtained by grinding whole corn with a hammermill and diets were offered in a crumbled form.

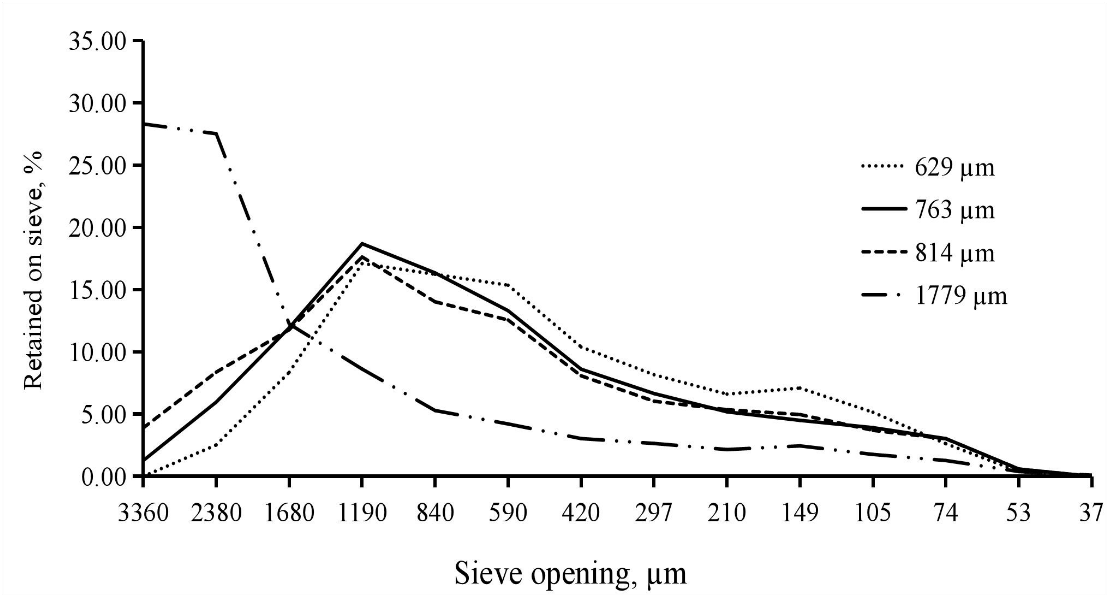

Figure 3.2 In trial 2, the geometric mean diameter by mass (D_{gw}) and particle size distribution of corn prior mixing during was determined in the grower period from 15 to 28 d of age. Ross × Ross 708 male broilers were fed 4 corn particle sizes over the grower period from 15 to 28 d of age (n=10). Dietary treatments were obtained by grinding whole corn with a hammermill (629, 763, and 814 µm) and a roller mill (1,779 µm). A common starter diet was fed during the starter period in a crumbled form from 1 to 14 d of age.

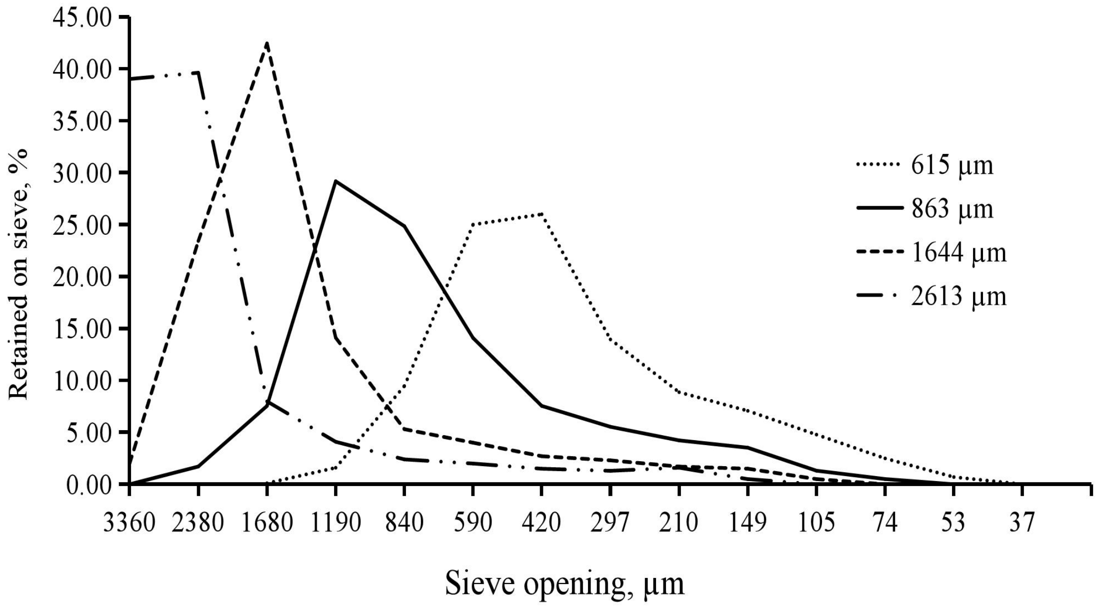

Figure 3.3 In trial 3, the geometric mean diameter by mass (D_{gw}) and particle size distribution of corn prior mixing during was determined in the finisher period from 28 to 42 d of age. Ross × Ross 708 male broilers were fed 4 corn particle sizes over the finisher period from 28 to 42 d of age (n=10). Dietary treatments were obtained by grinding whole corn with a roller mill (615, 863, 1,644 and 2,613 µm) and diets were offered in a pelleted form. Common starter and grower diets were fed from 1 to 14 and 14 to 28 d of age, respectively.

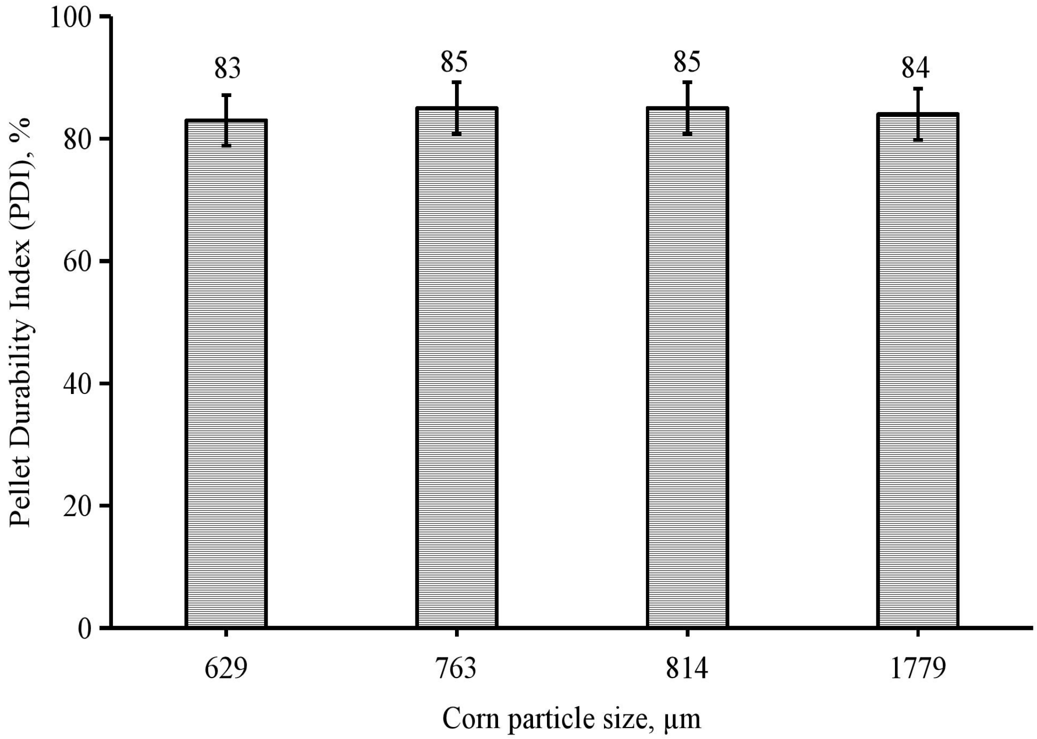

Figure 3.4 In trial 2, dietary treatments were obtained by grinding whole corn with a hammermill and a roller mill and diets were offered in a pelleted form. Ross × Ross 708 male broilers were fed 4 corn particle sizes over the grower period from 14 to 28 d of age. A common starter diet was fed during the starter period in a crumbled form from 1 to 14 d of age. The pellet durability index (PDI) was measured for the grower pellets from 14 to 28 d of age (n=16).

IV. EFFECTS OF FEED FORM ON GROWTH PERFORMANCE AND CARCASS CHARACTERISTICS OF BROILERS

ABSTRACT

An experiment (2 trials) was conducted to determine the effects of feeding Ross × Ross 708 male broilers diets in various feed forms on growth performance and carcass characteristics during the starter, grower, and finisher periods. In trial 1, 5 dietary treatments consisting of 3 feed forms were provided during the starter period: 1) mash from 1 to 14 d, 2) crumbles from 1 to 14 d, 3) 3.3 mm micro pellets from 1 to 4 d and then crumbles to 14 d, 4) 3.3 mm micro pellets from 1 to 7 d and then crumbles to 14 d, and 5) 3.3 mm micro pellets from 1 to 14 d mash, crumbles, and/or 3.3 mm micro pellets). Birds fed mash diets during the starter period had the lowest BW and feed intake at 14, 25, and 35 d compared with birds fed either crumbles and/or 3.3 mm micro pellets ($P < 0.05$). Moreover, birds fed mash diets during the starter period had higher feed conversion (**FCR**) at 14 and 25 d compared with birds that received either crumbles and/or 3.3 mm micro pellets during the starter period ($P < 0.05$). Birds fed 3.3 mm micro pellets from 1 to 7 and 1 to 14 d had higher breast meat weight compared with those fed mash diets during the starter period ($P < 0.05$). In trial 2, a 3 × 2 factorial arrangement of 3 feed forms (mash, 4.4 mm pellets, and 3.3 mm micro pellets) and 2 amino acid (AA) densities (88% and 96% of Aviagen recommendations) was provided from 1 to 42 d. Interactions were not apparent for the variables tested in this experiment ($P > 0.05$). Birds

fed 3.3 mm micro pellets and 4.4 mm pellet had higher BW, feed intake, improved FCR, carcass and breast meat weight than birds fed mash diets at 42 d ($P < 0.05$). In addition, birds fed diets with 96% of AA recommendations had higher BW, carcass yield, carcass and breast meat weight and lower FCR than birds fed diets with 88% ($P < 0.05$). Based on the results of this study, broilers can be fed 3.3 mm micro pellets and 4.4 mm pellets and 96% AA density during the starter period and/or during the whole production period to improve growth performance and meat accretion.

INTRODUCTION

Limitations in beak size of newly hatched chicks have led the majority of broiler integrators in the U.S. to feed crumbles during the pre-starter or starter period (Moran, 1982; Portella et al., 1988; Choi et al., 1986; Agah and Norollahi, 2008). However, previous research has reported that providing high quality micro pellets instead of crumbles during the starter period could be an alternative to improve early and subsequent growth performance of broilers (Quentin et al. 2004; Cerrate et al., 2008; Sundu et al., 2009; Roulleau et al., 2015). Broilers fed pelleted diets exhibit increased feed intake, average daily gain, carcass weight and decreased prehension time, feed wastage, nutrient segregation, and selective feeding (Jensen et al., 1962; Nir et al., 1994; Moritz et al., 2001; Lilly et al., 2011b). However, research evaluating the effect of 3.3 mm micro pellets on growth performance and processing yield is sparse.

Dietary amino acid (**AA**) requirements are higher in fast-growing broilers particularly when broilers are fed high quality pellets instead of mash (Choi et al., 1986; Kidd et al., 2004; Quentin et al., 2004; Corzo et al., 2012). In addition, previous research has reported that birds fed pelleted diets with higher dietary AA densities display improved growth performance compared with broilers fed mash diets (Greenwood et al., 2004, 2005; Lemme et al., 2006). However, despite the potential interactive effects of feed forms and AA densities, little research has been conducted evaluating the interactions of micro pellets and AA densities on growth performance of broilers. The evaluation of the interactive effects of high quality 4.4 mm pellets and 3.3 mm micro pellets in comparison to mash diets is crucial to optimize growth performance and increase carcass yield. Therefore, a study was conducted to determine the effects of feeding mash, crumbles, 4.4 mm pellets, 3.3 mm micro pellets, and varying dietary AA densities (88% and 96% of Aviagen AA recommendations) on growth performance and carcass characteristics of broilers during the starter, grower, and finisher periods.

MATERIALS AND METHODS

All procedures involving live birds were approved by Auburn University Institutional Animal Care and Use Committee (PRN 2014-2579) (PRN 2017-3127).

Husbandry Practices

In both trials, Ross × Ross 708 chicks (Aviagen North America, Huntsville, AL) were obtained from a commercial hatchery at 1 d of age. In trial 1, 1,000 broiler chicks were weighed and randomly distributed among 40 pens (25 birds/pen; 0.12 m^2/bird) in an environmentally controlled room. Birds and feed were weighed to determine BW, feed intake, and FCR at 1, 14, 25 and 35 d of age. In trial 2, 1,008 male broiler chicks were feather sexed, weighed and randomly distributed among 42 pens (24 birds/pen; 0.11 m^2/bird) in an environmentally controlled room. Birds and feed were weighed to determine BW, feed intake, and FCR at 1, 14, 28 and 42 d of age. Both trials were conducted in the same facility, which was equipped with exhaust fans, forced-air heaters, cooling pads, an electronic controller to adjust temperature, and ventilation. Each pen had 5 nipple drinkers and 1 tube feeder for *ad libitum* consumption of feed and water. The lighting program consisted of 23L:1D from 1 to 7 d, 21L:3D from 8 to 20 d and 16L:8D from 21 to 35 or 42 d. The room temperature was 35°C from 1 to 2 d of age, 31.3°C from 2 to 5 d of age, 29.4°C from 6 to 14 d of age and 28.3°C from 15 to 23 d of age, 26.7ºC from 24 to 28 d of age and 23.8ºC from 29 to 35 or 42 d of age. The incidence of mortality was recorded daily.

Feed Formulation, Manufacture, and Experiment Design

Broiler diets (Tables 4.1 and 4.2) were formulated to meet or exceed the NRC suggested minimum nutrient requirements of broilers (NRC, 1994). In trial 1, each pen was randomly assigned to 1 of 5 dietary treatments during the starter period: 1) mash from 1 to 14 d of age, 2) crumbles from 1 to 14 d of age, 3) 3.3 mm micro pellets from 1 to 4 d of age and then crumbles to 14 d of age, 4) 3.3 mm micro pellets from 1 to 7 d of age and then crumbles to 14 d of age, and 5) 3.3 mm micro pellets from 1 to 14 d of age represented by 8 replicate pens. Common grower and finisher diets were offered in a 4.4 mm pelleted form from 15 to 35 d of age. In trial 2, each pen was randomly assigned to 1 of 6 dietary treatments which consisted of a 3 x 2 factorial arrangement with 3 feed forms (mash, crumbles + 4.4 mm pellets, and 3.3 mm micro pellets) and 2 AA densities (88% and 96% of Aviagen AA recommendations). The dietary treatments were: 1) mash at 88% AA density from 1 to 42 d of age, 2) mash at 96% AA density from 1 to 42 d of age, 3) 3.3 mm micro pellets at 88% AA density from 1 to 42 d of age, 4) 3.3 mm micro pellets at 96% AA density from 1 to 42 d of age, 5) crumbles from 1 to 14 d of age and then 4.4 mm pellets at 88% AA density from 15 to 42 d of age, and 6) crumbles from 1 to

14 d of age and then 4.4 mm pellets at 96% AA density from 15 to 42 d of age represented by 7 replicate pens. 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 the mash diets, which were conditioned at 82°C for 45 s and then pelleted with a ring die (4.4 mm or 3.3 mm) using a pellet mill (Model 1112-4, California Pellet Mill Co., Crawfordsville, IN). In both trials, the length of the 3.3 mm micro pellets was adjusted to 3 mm using fixed knives to cut the micro pellets as they were extruded from the pellet mill die. Pellets were cooled with ambient air in a counter-flow pellet cooler (Model CC0909, California Pellet Mill Co., Crawfordsville, IN). The starter feed was crumbled in a crumbler with manual roll adjustment (Model 624SS, California Pellet Mill Co., Crawfordsville, IN).

Measurements

In trial 1, feed intake and BW by pen were recorded at 1, 14, 25 and 35 d of age. Birds were observed twice daily, and mortalities were removed and their BW was included in the FCR calculation. Feed was removed from each pen 10 hours prior to processing in both trials. At 36 d, 10 birds/pen were processed for the determination of carcass characteristics. The selected birds were placed in coops and transported to the Auburn University Pilot Processing Plant. Broilers were placed on shackles, electrically stunned, slaughtered, scalded, picked, and manually eviscerated. After processing, carcasses were chilled in slush ice for 4 hours before chilled carcass weights were determined. At 37 d, chilled carcasses were deboned to determine total breast meat yield (pectoralis major and minor muscles). In trial 2, feed intake and BW by pen were recorded at 1, 14, 28 and 42 d of age. Birds were observed twice daily, and mortalities were removed and their BW were included in the FCR calculation. At 43 d, 10 birds/pen were processed for the determination of carcass characteristics. After processing, carcasses were chilled in slush ice for 4 hours before chilled carcass weights were determined. At 44 d, chilled carcasses were deboned to determine total breast meat yield (pectoralis major and minor muscles). Carcass and total breast meat yields were calculated relative to live weight at 43 d of age (trial 2).

Statistical Analyses

Trial 1 was a randomized complete block design with pen location as the blocking factor. Each treatment was represented by 10 replicate pens with pen being the experimental unit. Mortality data were subjected to arcsine transformation before analysis. Data were analyzed as a one-way ANOVA using the GLM procedure of JMP software (SAS Institute Inc., Cary, NC) with the following model:

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

Where Y_{ij} = observed response of the bird in the pen; μ = is the overall mean; T_i = fixed effect of feed form treatment; and ε_{ij} = residual error when the pen was regarded as an experimental unit, $\varepsilon_{ij}\ N(0, \sigma^2_\varepsilon)$. The mean values among the 5 feed forms treatments were compared using the Tukey's honestly significant different procedure with statistical significance considered at $P \leq 0.05$ unless otherwise indicated.

In trial 2, results were analyzed as a 3 × 2 factorial (feed form × dietary AA) randomized complete block design. Each of the 6 treatments was represented by 7 replicates per pen. Pen location was the blocking factor. Mortality data were subjected to arcsine transformation before analysis. Data were analyzed using the GLM procedure of JMP software (SAS Institute Inc., Cary, NC) with the following mixed-effects model:

$$Y_{ij} = \mu + \rho_i + \tau_j + \varepsilon_{ij}$$

Where Y_{ij} = observed response of the bird in the pen; μ = is the overall mean; the ρi are identically and independently normally distributed random block effects with mean 0 and variance σ^2_ρ; the τj are fixed factor level effects corresponding to the j[th] dietary treatment (diets 1 to 6) such that $\sum\tau j = 0$; and the εij are identically and independently normally distributed random errors with mean 0 and a variance σ^2. The mean values among the 6 dietary treatments were compared using the Tukey's honestly significant different procedure with statistical significance considered at $P \leq 0.05$ unless otherwise indicated.

RESULTS

Trial 1

Growth performance data are presented in Table 4.3. Birds fed mash diets during the starter period had the lowest BW ($P < 0.05$) and feed intake ($P < 0.05$) at 14, 25, and 35 d of age compared with birds that received either crumbles and/or 3.3 mm micro pellets. Feed conversion at 14 d of age was significantly affected by the feed form. Birds fed mash diets exhibited higher FCR ($P < 0.05$) at 14 of age compared with birds that received either crumbles and/or 3.3 mm micro pellets during the starter period. However, birds fed 3.3 mm micro pellets from 1 to 14 d had lower FCR compared with birds fed crumbled diets during the starter period. Intermediate responses were observed on birds fed 3.3 mm micro pellets from 1 to 4 and 1 to 7 d at 14 d of age. However, after all chicks had been placed on a common 4.4 mm pelleted diet, FCR at 25 d of age did not differ among birds fed 3.3 mm micro pellets and similar responses were starting to be observed with those fed crumbled and mash diets during the starter period. Indeed, FCR at 35 d of age was not significantly affected by the dietary treatments fed during the starter period ($P > 0.05$). There was no significant effect of feed form on mortality ($P > 0.05$).

Carcass characteristics data are presented in Table 4.4. Carcass weight ($P < 0.05$) at 35 d of age was significantly higher on birds fed 3.3 mm micro pellets from 1 to 4 and from 1 to 7 d of age compared with birds fed mash. A similar response was observed in breast meat weight ($P < 0.05$) on birds fed 3.3 mm micro pellets from 1 to 7 and from 1 to 14 d of age compared with mash diets. Crumbled diets fed during the starter period produced an intermediate carcass and breast meat weight at 35 d of age. The weight of tenders responded in a manner similar to the weight of carcass, the 3.3 mm micro pellets led to an increase in tender's weight compared with mash but had similar responses with crumbled diets. There was no significant effect of feed form on tenders and breast meat yield ($P > 0.05$).

Trial 2

Feed form and dietary AA density only interacted for effects on FCR during the starter period from 1 to 14 d of age ($P < 0.05$) (Figure 4.1). Birds fed 3.3 mm micro pellets at 96% AA density had approximately 11 points better FCR ($P < 0.05$) compared with birds fed crumbled diets at 88% AA density. Feeding crumbled diets at 96% AA density had similar FCR with the 3.3 mm micro pellets at 88% AA density. However, reducing dietary AA density from 96 to 88% in crumbled diets produced similar responses in FCR compared with mash diets at 96% AA density.

The main effects of feed form and AA density on growth performance are presented in Table 4.5. Birds fed mash diets had lower BW ($P < 0.05$), feed intake ($P < 0.05$) and higher FCR ($P < 0.05$) compared with those that received either crumbles and/or 3.3 mm micro pellets from 1 to 42 d of age. A higher BW ($P > 0.05$) and lower FCR ($P < 0.05$) were observed on birds fed 3.3 micro pellets compared with those fed crumbles and mash diets at 14 d of age. Although similar responses were expected in subsequent periods, there were no statistical differences between birds fed 3.3 mm micro pellets or crumbles from 1 to 14 d and then 4.4 mm pellets on these parameters at 28 and 42 d of age. Feed form did not affect the incidence of mortality ($P > 0.05$).

When the entire experimental period was evaluated (1 to 42 d), even though dietary AA densities did not influence feed intake ($P > 0.05$), birds that received 96% AA density had higher BW ($P < 0.05$) and lower FCR ($P < 0.05$) compared with birds fed 88% AA density. Birds fed 96% AA density had higher mortality ($P < 0.05$) than birds fed 88% at 14 d of age but no differences were observed at 28 and 42 d of age ($P > 0.05$).

The main effects of feed form and AA density on carcass characteristics of broilers are presented in Table 4.6. Birds fed 3.3 mm micro pellets from 1 to 42 d or crumbles from 1 to 14 d and then 4.4 mm pellets from 15 to 42 d had higher carcass, tenders, wings, and breast meat weight ($P < 0.05$) compared with birds fed mash diets from 1 to 42 d of age. Although birds fed the 3.3 mm micro pellets had higher breast meat yield ($P < 0.05$) compared with those fed mash diets, intermediate responses were observed on birds fed crumbled diets. In terms of dietary AA densities, feeding 96% of dietary AA density produced higher carcass, tenders, wings and breast meat weight ($P < 0.05$) compared to 88% dietary AA density. Although no significant differences in carcass yield ($P > 0.05$) were observed between AA densities, decreasing AA density from 96% to 88% reduced total breast meat yield by 0.8 percentage points ($P < 0.05$).

DISCUSSION

In both trials, greater BW and feed intake were observed in birds fed crumbles, 3.3 mm micro pellets, and 4.4 mm pellets compared to mash diets during the entire experimental period. These data indicated that pelleted diets increase BW and feed intake during the starter period and in subsequent periods of broilers regardless of the diameter compared to mash diets, a finding consistent with previous studies (Quentin et al., 2004; Brickett et al., 2007; Cerrate et al., 2008, 2009; Serrano et al., 2012; Abdollahi et al., 2013a, b). These findings have been associated to a greater digestibility of nutrients and less feed wastage on birds fed pellets compared with mash diets (Amerah et al., 2007). However, the present study was conducted on floor pens and feed wastage was not observed on birds fed mash diets. In trial 2, the fact that birds fed 3.3 mm micro pellets had higher BW at 14 d of age than those fed crumbled and mash diets suggests the potential benefits of feeding a micro pellet during the starter period. Previous research has suggested that feeding crumbled diets rather than intact micro pellets may motivate newly hatched chicks to spend more time and energy selecting coarse feed particles, which can directly influence BW during this period (Michard and Rouxel, 2013). Roulleau et al. (2015) reported that broilers fed 2.2 mm micro pellets had 4.3 and 6.5% higher BW at 9 and 20 d compared with birds fed crumbled diets. However, Cerrate et al. (2009) reported no statistical differences in BW of broilers fed crumbles, 1.59 mm or 3.17 mm pellets during the starter period from 1 to 13 d. The fact that a numerical increase in BW was observe in favor of the 3.3 mm micro pellets until 28 d but not at 42 d of age suggests that a 4.4 mm pellet size should be fed in the grower and finisher periods to promote growth performance. However, more research is warranted in this area. Sundu et al. (2009) suggested that a larger pellet size is required as the bird ages to maintain growth performance. In addition, this negative aspect of the 3.3 mm micro pellets could be overcome by increasing their length in order to compensate for the smaller diameter.

During the starter period, a lower FCR was observed in both trials on birds that received 3.3 mm micro pellets compared with crumbles and/or mash diets. In trial 1, based on the beneficial effects of feeding 3.3 mm micro pellets in FCR from 1 to 14 d, it was expected to observe greater improvements in the grower and finisher periods after feeding 4.4 mm pelleted diets. However, this positive effect did not happen. Previous research has reported that feeding common pelleted diets during the grower and finisher periods preclude the benefits of lower FCR observed in the starter period when crumbles are fed in comparison to mash diets (Choi et al., 1968; Scott, 2002). Cerrate et al. (2008) reported that broilers fed 2.38 mm and 3.17 mm pellets had lower FCR compared with broilers fed mash, crumbles, and 1.59 mm pellets at 7 d of age; however, no differences were reported at 14 and 35 d of age after broilers received a common crumbled and 4.76 mm pelleted diet from 7 to 35 d of age. A subsequent study, reported that broilers fed mash, crumbles, 1.59 mm pellets, and 3.17 mm pellets during the starter period from 1 to 13 d had no differences in FCR at 34 and 41 d of age after they received common 4.76 mm pelleted diet (Cerrate et al., 2009). The authors concluded that birds have a compensatory growth after they receive common pelleted diets in subsequent periods. However, in trial 1, this effect may be attributable to a lower feed intake of birds fed mash diets during the starter period compared with the grower and finisher periods.

Interactions between feed form and AA density observed in the second trial provide a better understanding of bird positive responses in FCR when feeding 3.3 mm micro pellets compared with crumbled and mash diets during the starter period. Crumbled diets improved FCR only when dietary AA density increased from 88% to 96%, whereas lowering dietary AA density produced similar responses with mash diets at 96% AA density. The higher FCR observed in crumbled diets at 88% AA density suggests that intake of dietary dispensable AAs such as lysine (**Lys**) is reduced when pellets are broken down into granules. In addition, particle size preference of broilers may lead to selective feeding in crumble diets which reduces essential nutrient intake (Portella et al., 1988). Brickett et al. (2007) reported that a lower nutrient density (total dietary Lys balanced to dietary energy) in mash and pelleted diets have a greater impact in FCR compared with a high nutrient density diet. Therefore, it is important to provide optimum dietary Lys levels during the starter period hence improve growth performance in subsequent phases (Kidd et al., 1998). On the other hand, birds fed 3.3 mm micro pellets at 96% AA density had a significant reduction in FCR compared with crumbled and mash diets regardless of their AA density. Greenwood et al. (2005) reported that birds fed pelleted diets increased lysine consumption at each level of digestible lysine (0.75, 0.85, 0.95, 1.05, and 1.15%) compared with birds fed coarse mash diets. Although a higher AA density is required to improve FCR with the 3.3 mm micro pellets compared with crumbled diets, previous researchers have suggested that increasing dietary AA content during the pre-starter and starter periods could be a cost-effective strategy to allow birds to build protein reserves that can be used in subsequent phases (Kidd et al., 2004; Dozier et al., 2008). Based on the current results, it may be speculated that feeding micro pellets to newly hatched chicks agglomerate essential nutrients required during the starter period which may promote growth performance at an early stage.

The results of trial 2 are in agreement with previous studies in which diets with higher AA density improved BW and FCR of broilers during a 42 d production period (Kidd et al., 1998; Corzo et al., 2004; Greenwood et al., 2005; Kidd et al., 2005; Dozier et al., 2007; Lilly et al., 2011a). However, feed intake was not a sensitive response during the experimental period. Previous research has reported that dietary AA densities significantly influence feed intake of broilers (Greenwood et al., 2005; Brickett et al., 2007; Corzo et al., 2012). However, the confounding results observed in feed intake from previous research may be related to the different dietary AA content used to conduct the studies and likely the age of the bird which can interfere with the results.

Carcass characteristics agreed with the responses observed for live performance. In parallel with BW at 35 and 42 d of age in both trials, carcass weight was lower in birds fed mash diets compared with those fed crumbles, 3.3 mm micro pellets and 4.4 mm pellets. In both trials, breast and carcass meat weight, appeared to be one of the carcass traits most sensitive to feed form. In trial 1, the fact that birds fed 3.3 mm micro pellets during the starter period improved carcass and breast meat weight suggests that micro pellets provide dietary dispensable AAs required for meat deposition. It has been reported that Lys content is critical for muscle development and breast meat deposition in broilers (Dozier et al., 2008). Indeed, previous research has reported that adequate AA concentrations in broiler diets are important to optimize protein accretion and increase meat yield (Sibbald and Wolynetz, 1986; Kidd et al., 2004). In trial 2, although no interactions between feed form and AA density were observed in carcass characteristics, the main effects showed that pelleted diets and a 96% AA density positively influence breast meat yield. Therefore, as observed in the live performance data, feeding 3.3 mm micro pellets during the starter period may also promote carcass and breast meat weight of broilers.

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Table 4.1 Ingredient and nutrient composition of dietary treatments fed to Ross × Ross 708 male broilers from 1 to 35 d of age, trial 1

Ingredient, % "as-fed"	Starter	Grower	Finisher
Corn	51.96	58.83	61.88
Soybean Meal, 46 % Crude Protein	35.97	27.56	23.14
Distillers dried grains with solubles (DDGS)	5.00	7.00	9.00
Poultry Oil	3.40	3.33	3.45
Dicalcium phosphate, 18% P	1.27	0.97	0.48
Calcium carbonate	1.24	1.16	1.02
Sodium chloride	0.37	0.37	0.28
D-L Methionine	0.28	0.25	0.20
L-Lysine	0.12	0.17	0.18
Trace mineral premix[1]	0.10	0.10	0.10
Vitamin premix[2]	0.10	0.10	0.10
Choline Chloride	0.08	0.07	0.08
L-Threonine	0.04	0.06	0.06
Copper chloride[3]	0.02	0.02	0.02
Quantum phytase[4]	0.01	0.01	0.01
	100.00	100.00	100.00
Calculated analysis, % (unless otherwise noted)			
AME_n, kcal/kg	3,025	3,117	3,175
Crude Protein	23.24	20.45	19.01
Digestible Lys	1.18	1.02	0.95
Digestible Thr	0.77	0.68	0.63
Digestible Trp	0.23	0.19	0.18
Digestible TSAA[5]	0.91	0.78	0.72
Calcium	1.00	0.88	0.76
Available phosphorus	0.48	0.42	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]Intellibond ® C (Micronutrients, Indianapolis, IN).
[4]Quantum® Blue 5G (AB Vista Feed Ingredients, Marlborough, UK) provides per kg of diet: 500 FTU/kg of phytase activity.
[5]TSAA = Total sulfur amino acids

Table 4.2 Ingredient and nutrient composition of dietary treatments of varying in amino acid (AA) density fed to Ross × Ross 708 male broilers from 1 to 42 d of age, trial 2

	Starter		Grower		Finisher	
AA density	88%	96%	88%	96%	88%	96%
Ingredient, % "as-fed"						
Corn	59.21	53.28	63.77	58.53	65.11	60.28
Soybean Meal, 46 % Crude Protein	33.41	38.40	26.62	31.04	21.71	25.78
Distillers dried grains with solubles (DDGS)	3.00	3.00	6.00	6.00	9.00	9.00
Vegetable Oil	1.15	2.14	0.65	1.53	1.54	2.35
Dicalcium phosphate, 18% P	1.01	0.97	0.73	0.69	0.49	0.45
Calcium carbonate	1.11	1.10	1.11	1.10	1.08	1.07
Sodium chloride	0.36	0.36	0.35	0.35	0.33	0.33
D-L Methionine	0.28	0.32	0.23	0.26	0.19	0.22
L-Lysine	0.13	0.11	0.18	0.16	0.21	0.19
Trace mineral premix[1]	0.10	0.10	0.10	0.10	0.10	0.10
Vitamin premix[2]	0.05	0.05	0.05	0.05	0.05	0.05
Choline Chloride, 70%	0.08	0.06	0.09	0.07	0.10	0.08
L-Threonine	0.07	0.08	0.07	0.08	0.07	0.08
Copper chloride[3]	0.02	0.02	0.02	0.02	---	---
Phytase[4]	0.01	0.01	0.01	0.01	0.01	0.01
Econase[5]	0.01	0.01	0.01	0.01	0.01	0.01
	100.00	100.00	100.00	100.00	100.00	100.00
Calculated analysis, % (unless otherwise noted)						
AME_n, kcal/kg	3,025	3,025	3,100	3,100	3,185	3,185
Crude Protein[6]	21.20	23.11	19.18	20.87	17.80	19.36
Digestible Lys	1.12	1.23	1.01	1.10	0.93	1.01

Digestible Thr	0.75	0.82	0.67	0.73	0.62	0.68
Digestible Trp	0.22	0.24	0.19	0.21	0.16	0.18
Digestible TSAA[6]	0.85	0.93	0.76	0.83	0.70	0.77
Total Lysine, %	1.24	1.36	1.12	1.22	1.03	1.13
Total Methionine + cysteine, %	0.93	1.02	0.84	0.92	0.78	0.85

[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]Intellibond® C (Micronutrients, Indianapolis, IN).

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

[5]Econase XT 25 (AB Vista Feed Ingredients, Marlborough, UK) provides per kg of diet: 16,000 BXU/kg of xylanase activity.

[6]TSAA = Total sulfur amino acids

Table 4.3 Growth performance of Ross × Ross 708 male broilers provided diets varying in physical feed form from 1 to 35 d of age, trial 1

Item	BW, g/bird[2]			Feed intake, g/bird			FCR, g:g[3]			Mortality, %[5]		
	Days of Age											
Dietary Treatments[1]	14	25	35	14	25	35	14	25	35	14	25	35
Mash	384^{b}	1,181^{b}	2,380^{b}	481^{b}	1,557^{b}	3,555^{b}	1.405^{a}	1.377^{a}	1.526	0.5	2.0	0.0
Crumble	443^{a}	1,297^{a}	2,482^{a}	516^{a}	1,690^{a}	3,708^{a}	1.281^{b}	1.347^{ab}	1.520	0.0	1.0	1.0
3.3 mm Micro pellets (1-4 d)	446^{a}	1,302^{a}	2,496^{a}	510^{a}	1,692^{a}	3,723^{a}	1.255^{bc}	1.345^{b}	1.520	0.0	2.0	1.0
3.3 mm Micro pellets (1-7 d)	454^{a}	1,303^{a}	2,495^{a}	515^{a}	1,698^{a}	3,733^{a}	1.256^{bc}	1.348^{b}	1.527	0.0	1.0	1.0
3.3 mm Micro pellets (1-14 d)	453^{a}	1,281^{a}	2,442^{ab}	509^{a}	1,670^{a}	3,652^{ab}	1.236^{c}	1.340^{b}	1.533	0.0	1.0	2.0
SEM[4]	5	10	24	5	15	33	0.010	0.007	0.010	0.002	0.008	0.006
P-value	0.001	0.001	0.008	0.001	0.001	0.003	0.001	0.008	0.872	0.420	0.793	0.405

[a-b]Means within a column with different superscripts differ significantly ($P < 0.05$).

[1]Treatments consisted of mash (1-14 d), crumbles (1-14 d), 3.3 mm micro pellets (1-4 d) and then crumbles, 3.3 mm micro pellets (1-7 d) and then crumbles, and 3.3 mm micro pellets (1-14 d). Common grower and finisher diets were offered in a 4.4 mm pelleted form from 15 to 35 d of age.

[2]BW= Body Weight.

[3]Feed conversion ratio was corrected for mortality.

[4]SEM= Standard error of the means for feed form effect (n=8).

[5]Mortality values were arcsin transformed.

Table 4.4 Carcass weight and tenders and breast meat yields of Ross × Ross 708 male broilers provided diets varying in physical feed form from 1 to 35 d of age, trial 1

Item	Carcass	Tenders		Breast Meat	
	Weight, g	Weight, g	Yield[2], %	Weight, g	Yield, %
Dietary treatments[1]					
Mash	1,721[b]	98[b]	5.71	488[b]	28.35
Crumble	1,785[ab]	104[ab]	5.84	511[ab]	28.60
3.3 mm Micro pellets (1-4 d)	1,805[a]	104[ab]	5.76	512[ab]	28.30
3.3 mm Micro pellets (1-7 d)	1,810[a]	105[a]	5.81	520[a]	28.67
3.3 mm Micro pellets (1-14 d)	1,783[ab]	103[ab]	5.80	518[a]	29.04
SEM[3]	165	15	0.669	64	2.04
P-value	0.006	0.038	0.791	0.018	0.169

[a-b]Means within a column with different superscripts differ significantly ($P < 0.05$).
[1]Treatments consisted of mash (1-14 d), crumbles (1-14 d), 3.3 mm micro pellets (1-4 d) and then crumbles, 3.3 mm micro pellets (1-7 d) and then crumbles, and 3.3 mm micro pellets (1-14 d). Common grower and finisher diets were offered in a 4.4 mm pelleted form from 15 to 35 d of age after dietary treatments.
[2]Yield was computed by dividing tenders and breast weight and by carcass weight and multiplying by 100.
[3]SEM= Standard error of the means for feed form (n=10).

Table 4.5 Growth performance of Ross × Ross 708 male broilers provided diets varying amino acid (AA) density and physical feed form from 1 to 42 d of age, trial 2[1]

Item	BW, g/bird[2]			Feed intake, g/bird			FCR, g:g[3]			Mortality, %[6]		
	Days of Age											
	14	28	42	14	28	42	14	28	42	14	28	42
Main effect												
Physical feed form												
Mash	394[c]	1,374[b]	2,752[b]	446[b]	1,942[b]	4,342[b]	1.271[a]	1.470[a]	1.617[a]	1.7	2.0	0.2
3.3 mm Micro pellets	511[a]	1,713[a]	3,142[a]	540[a]	2,270[a]	4,740[a]	1.147[c]	1.371[b]	1.548[b]	0.8	2.6	1.4
4.4 mm Pellet	493[b]	1,677[a]	3,155[a]	548[a]	2,184[a]	4,731[a]	1.216[b]	1.353[b]	1.531[b]	1.0	3.5	1.7
SEM[4]	4	14	32	4	38	35	0.005	0.023	0.013	0.005	0.009	0.006
AA density[5]												
88%	459[b]	1,557[b]	2,953[b]	513	2,126	4,588	1.231[a]	1.417	1.592[a]	0.5[b]	2.7	1.1
96%	473[a]	1,618[a]	3,080[a]	510	2,138	4,620	1.192[b]	1.380	1.538[b]	2.1[a]	2.7	1.1
SEM[4]	3	12	26	4	31	28	0.004	0.019	0.010	0.004	0.007	0.005
Source of variation	--*P-value*--											
Feed Form	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.554	0.517	0.220
AA density	0.001	0.001	0.001	0.481	0.784	0.441	0.001	0.182	0.001	0.024	1.000	1.000

[a-b]Means within a column with different superscripts differ significantly ($P < 0.05$).

[1]Treatments consisted of mash, 3.3 mm micro pellets, and 4.4 mm pellets at 88% and 96% AA density.

[2]BW= Body Weight.

[3]Feed conversion ratio was corrected for mortality.

[4]SEM= Standard error of the means for feed form and AA density effect (n=14).

[5]AA densities at 88% and 96% of Aviagen Recommendations.

[6]Mortality values were arcsin transformed.

Table 4.6 Carcass and breast meat yields of Ross × Ross 708 male broilers provided diets varying in amino acid (AA) and physical feed form from 1 to 42 d of age, trial 2[1]

Item	Carcass		Breast Tenders		Wings		Breast Meat	
	Weight, g	Yield[2], %	Weight, g	Yield, %	Weight, g	Yield, %	Weight, g	Yield, %
Main Effect								
Physical Feed Form								
Mash	2,108[b]	76.33	125[b]	5.94	217[b]	10.36	613[b]	29.06[b]
3.3 mm Micro pellets	2,456[a]	76.82	141[a]	5.77	247[a]	10.12	732[a]	29.93[a]
4.4 mm Pellet	2,435[a]	76.69	141[a]	5.84	247[a]	10.17	723[a]	29.70[ab]
SEM[3]	19	0.61	2	0.07	2	0.07	7	0.26
AA density[4]								
88%	2,281[b]	76.66	132[b]	5.80	233[b]	10.27	664[b]	29.16[b]
96%	2,385[a]	76.53	140[a]	5.90	242[a]	10.16	713[a]	29.97[a]
SEM[3]	16	0.50	1	0.05	2	0.06	6	0.21
Source of variation	--*P-value*--							
Feed Form	0.001	0.841	0.001	0.228	0.001	0.077	0.001	0.050
AA density	0.001	0.885	0.001	0.215	0.001	0.250	0.001	0.007

[a-b]Means within a column with different superscripts differ significantly ($P < 0.05$).

[1]Treatments consisted of mash, 3.3 mm micro pellets, and 4.4 mm pellets at 88% and 96% AA density.

[2]Yield was computed by dividing weight of the carcass, breast fillets, wings and breast tenders by BW and multiplying by 100.

[3]SEM= Standard error of the means for feed form and AA density effect (n=14).

[4]AA densities at 88% and 96% of Aviagen Recommendations.

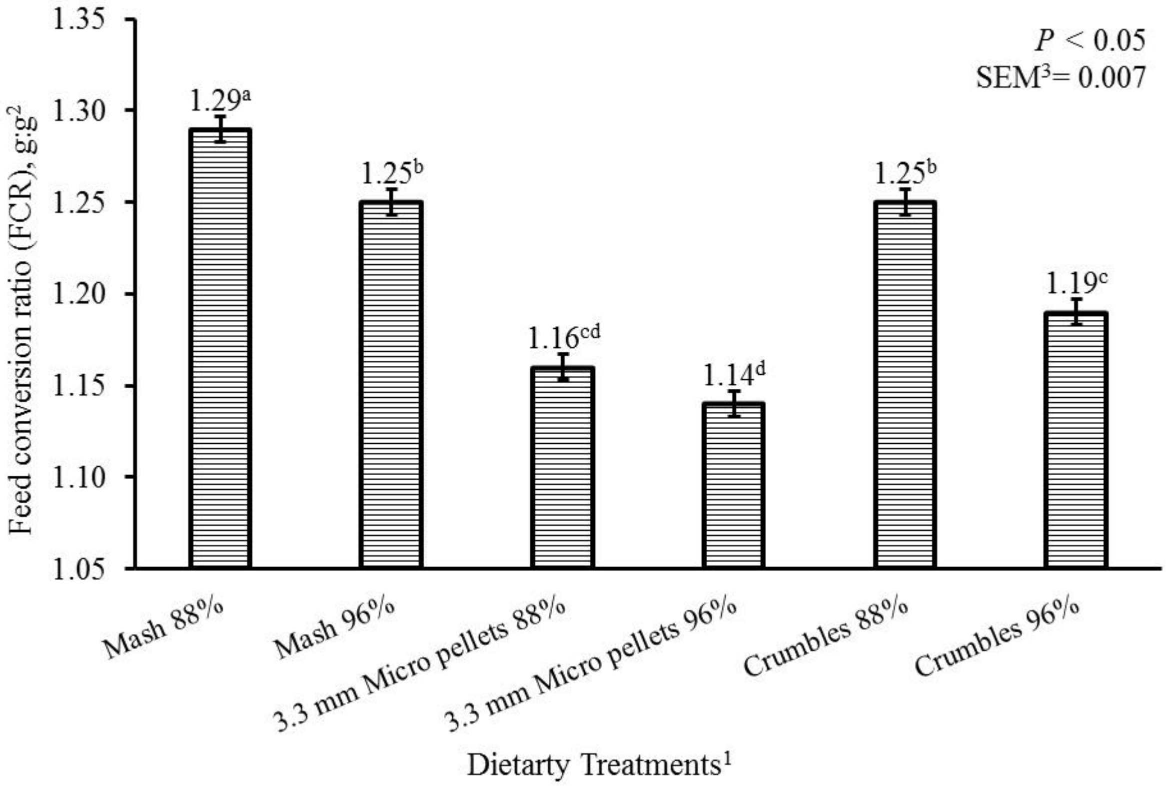

Figure 4.1 Feed conversion ratio (FCR) of Ross × Ross 708 male broilers provided diets varying in amino acid (AA) density (88% and 96% of Aviagen Recommendations) and physical feed form during the starter period from 1 to 14 d of age, trial 2.

[a-b]Means within a column with different superscripts differ significantly ($P < 0.05$).

[1]Treatments consisted of mash at 88% and 96% AA density, 3.3 mm micro pellets at 88% and 96% AA density, and crumbles followed by 4.4 mm pellets at 88% and 96% AA density.

[2]Feed conversion ratio was corrected for mortality.

[3]SEM= Standard error of the means for feed form and AA density effect (n=14).

V. CONCLUSIONS

Corn particle size and feed form manipulation could be used as alternatives to improve growth performance in modern broiler production. Diets formulated with a coarser corn particle size have been reported to have beneficial effects in gizzard stimulation through reverse peristalsis which helps to re-expose digesta to gastric secretions and enzymes. In addition, grinding corn to a coarser particle size reduces energy consumption within the manufacturing process which reduces total feed costs.

The first experiment (3 trials) was designed to evaluate the effects of feeding diets with different corn particle size on broiler growth performance parameters. The particle size of corn was adjusted by using a hammermill and a roller mill, these diets were fed in the starter, grower and finisher periods of broilers (trial 1: 674, 741, 805, and 912 µm, trial 2: 629, 763, 814, and 1,779 µm, and trial 3: 615, 863, 1,644, and 2,613 µm). In trials 1 and 2, BW, feed intake, and FCR were maintained regardless of the particle size of corn in the diets during the starter from 1 to 14 d and grower from 14 to 28 d periods. Broilers were able to consume diets with a corn particle size of 912 µm and 1,779 µm during the starter and grower period respectively, without any adverse effects in growth performance, which may facilitate intake of coarser (> 1,000 µm) particles in subsequent phases. In trial 3, no differences in BW and feed intake were observed as the particle size of corn increased from 600 to 2,000 µm at 42 d of age. Nevertheless, broilers fed diets with a corn particle size of 1,644 µm had the highest feed intake compared to all dietary treatments from 28 to 42 d of age. At 42 d, broilers fed diets with a corn particle size larger than 1,000 µm compromised FCR compared to diets with a corn particle size of 615 and 863 µm. It was concluded that this effect may be attributable to the particle size of corn used in the common diets fed during the starter and grower periods (650 µm), which likely did not stimulate the gizzard function and did not prepare the GIT to adapt to a coarser particle size during the finisher period. Therefore, further research is necessary during the finisher period of broilers by providing coarser corn particle size (> 650 µm) in the starter and grower periods.

Due to limited published research on the effects of micro pellets beyond the starter period, the second experiment (2 trials) was conducted to evaluate broiler responses to various feed forms and dietary AA densities. In trial 1, dietary treatments consisted of various feed forms (mash from 1 to14 d of age, crumbles from 1 to14 d of age, and 3.3 mm micro pellets from 1 to14 d of age, 3.3 mm micro pellets from 1 to 4 d of age and then crumbles, and 3.3 mm micro pellets from 1 to 7 d of age and then crumbles) fed during the starter period followed by a common 4.4 mm pelleted diet fed from 15 to 35 d of age. Previous research has reported that feeding micro pellets to newly hatched chicks promotes growth rate during the starter period. In trial 1, mash diets fed during the starter period negatively influenced BW and feed intake of broilers compared to the 3.3 mm micro pellets and crumbles. Feed conversion at 14 d of age was lower on birds fed 3.3 mm micro pellets from 1 to 14 d than birds fed crumbles. Beneficial effects observed in FCR during the starter period with the 3.3 mm micro pellets as compared with crumbles disappeared once the birds were fed a 4.4 common pelleted diet in the grower and finisher periods. Indeed, no differences were observed in FCR at 35 d of age, which may be attributable to the lower feed intake occurred during the starter period.

Although birds fed crumbles and 3.3 mm micro pellets during the starter period had similar growth performance, carcass and breast meat weight were improved at 35 d when birds received 3.3 mm micro pellets from 1 to 7 and 1 to 14 d of age. In trial 2, a combination of 3 feed forms and 2 dietary AA densities (mash, 3.3 mm micro pellets, and crumbles + 4.4 mm pellets at 88% and 96% AA of Aviagen Recommendations) were provided to evaluate broiler growth performance and carcass characteristics in the starter, grower, and finisher periods from 1 to 42 d of age. Although no interactions were observed in growth performance between all dietary treatments in the grower and finisher periods, birds fed 3.3 mm micro pellets at 96% of dietary AA density exhibited lower FCR compared with those fed crumbled and mash diets at 88% during the starter period. In addition, lowering dietary AA content in crumbled diets may generate a higher FCR similar to mash diets during the starter period. Although not conclusive, based on the current results, it may be speculated that in order to obtain the same effects in FCR of the 3.3 mm micro pellets, crumbled diets must be formulated at a higher AA content in the starter period. Broilers fed 3.3 mm micro pellets and crumbles followed by 4.4 mm pellets increased BW and feed intake compared to mash treatments from 1 to 42 d of age. Similar with the results of trial 1, FCR improved on birds fed 3.3 mm micro pellets compared with crumbled and mash diets at 14 d of age, but no differences were observed at 28 and 42 d of age. Birds fed 96% of dietary AA density exhibited higher BW and lower FCR during the entire experimental period compared with those fed 88%. However, feed intake was not a sensitive response from 1 to 42 d of age. Carcass and breast meat weight was higher on birds that were fed 3.3 mm micro pellets, 4.4 mm pellets and 96% of AA density from 1 to 42 d of age. These data demonstrated that feeding 3.3 mm micro pellets and 4.4 mm pellets at 96% of dietary AA density could be an alternative to improve growth performance and carcass characteristics of broilers during a 42 d production period.