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Determination of the Optimal Starter Particle Size for Improved Starter and Overall Broiler Performance

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Determination of the optimal starter particle size for improved starter and overall broiler performance

By

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Determination of the optimal starter particle size for improved starter and overall broiler performance

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It is appreciated that improvements in feed form (FF) result in improved broiler performance. However, research has primarily focused on the finishing growth phase due to associated high feed consumption allowing the greatest opportunity to observe performance benefits. Due to lower feed volumes required in the starter growth phase, it may be more economical to improve FF in the starter phase if improvements in overall performance and processing characteristics are observed. Study 1 investigated the potential for interactive effects of high or low FF presented in each of three growth phases to influence broiler performance. These data demonstrated the potential for FF presented in the starter phase to interact with FF in the finisher phase influencing day (d) 46 ending body weight (BW). Due to starter FF impacting overall performance, this led to Study 2 which consisted of two experiments with the main objective of determining the optimal crumble particle size for improved starter (d 0-14) performance. Experiment 1 utilized 5 different crumble particle sizes ranging from 1202- 2172 µm; whereas Experiment 2 implemented 8 differing crumble particle sizes ranging from 1174- 3736

µm. These data demonstrated consistent improvements in feed conversion ratio (FCR) as crumble particle size increased, with improvements in BW gain being demonstrated in Experiment 2 for crumbles 2800 µm and larger. Due to associated performance benefits with large particle sizes, Study 3 examined the potential to feed pellets, in comparison to crumbles, at different qualities during the starter period. Additionally, two commonly used genetic strains were employed to determine if performance benefits due to FF and feed quality (FQ) would be similar among different strains. Lastly, common diets were fed following the starter phase to determine if benefits due to starter FF would translate to improved overall performance. Feed quality and FF interacted to influence d 18 BW and d 0-18 BW gain. Examining carryover effects, d 0-32 and 0-46 FCR were influenced by FF and FQ; whereas d 0-62 was not influenced. These data suggest that length of the growout should be considered for determining FQ and FF to present in the starter growth phase.

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CHAPTER I

LITERATURE REVIEW

World Population/Food Security

One pressing issue currently facing this world today is food security. With world populations increasing at unprecedented rates annually, the ever-increasing necessity to feed these people becomes a monumental task at the forefront of many agriculturist's minds. Estimates from the United Nations predict the world population to reach 9.7 billion people in 2050 from the current 7.3 billion [1]. Decreasing agricultural land, coupled with increasing populations, further complicate the conundrum of fulfilling our food demands [2]. Therefore, it is up to agriculturalist to create innovative strategies to maintain food security on a global scale. One promising solution to meet this increased demand is the production of poultry and poultry products. This is primarily due to poultry's highly efficient conversion of feed to consumable protein in comparison to other production animals.

Poultry Production

Due to poultry being a readily available product that is healthy and low-cost, poultry consumption has continuously increased in recent decades. Specifically, poultry meat is the second most consumed protein source worldwide making it a viable source to meet the global demand [3]. Furthermore, in the United States, poultry meat has been the most consumed protein source in the United States for the past two decades with an

average consumption (per capita) of 107 lbs. annually in 2016 [4]. The majority of this total poultry consumption was associated with broilers (chickens raised for meat), which comprised 90 lbs. of the total poultry consumption. Therefore, poultry production has a dramatic impact on the United States agricultural sector. Specifically, the poultry industry in the United States produced ~$38.7 billion of sellable products in 2016, with broilers making up the large majority of this value [5]. Commercial broilers were valued at a production value of $25.9 billion (~67% of total poultry production value) with 8.7 billion head of broilers being slaughtered to result in 54.3 billion lbs. of consumable meat [5]. While broiler production plays a vital role to the United States agricultural economy, it is particularly important for the southeastern United States where the majority of the broilers are raised. Georgia, Alabama, Arkansas, North Carolina, and Mississippi were the top 5 states (respectively) for broiler production in 2016, which are all located in the southeastern "broiler belt" [5]. Due to the author's location in Mississippi, the author will primarily focus on the Mississippi poultry industry in the next section.

Mississippi Poultry Production

As previously stated, poultry production plays a vital role to Mississippi's agricultural sector. Poultry products in 2016 resulted in a $2.7 billion value; with $2.2 billion being associated with broilers. This resulted in one third of the total value of agriculture production ($6.4 billion) for the state of Mississippi in 2016 [6]. Although the production values are impressive, the economic impact of poultry within the state is even more staggering with a total $18.4 billion economic value [7]. Due to the nature of this dissertation focusing on broiler production, the remainder of this literature review will primarily focus on the broiler industry. Six commercial integrators producing broilers

operate in the state of Mississippi. These include Koch Foods, Mar-Jac Poultry (formerly Marshall Durbin), Peco Foods Inc., Sanderson Farms Inc., Tyson Foods Inc., and Wayne Farms LLC. While the direct role of these companies on agricultural production value is apparent, it cannot be understated the indirect role these companies play within the state. One of these indirect roles being the contracting of growers for production of poultry, which has been estimated to surpass 1,400 farmers [7]. These contract growers play a vital role in production and are a critical step in maintaining vertical integration.

Vertical Integration

The majority of commercial broiler operations in the United States implement vertical integration [8]. Vertical integration is a management strategy in which one company will own all phases of operation including the hatchery, feed mill, processing plant, and marketing/distribution. Employing vertical integration provides the opportunity for implementation of the greatest quality control for each stage of production while reducing the investment cost since operations are on a larger economic scale. While most stages are owned by the parent company, the commercial houses in which the broilers are reared are not owned by the company, necessitating the need to contract growers. These contract growers are responsible for the management, maintenance of houses, and energy costs associated with raising broilers. The company will provide management advice through service technicians employed by the company, as well as chicks and feed and the transportation of each of these commodities throughout the entire growout. While the growers may not be shareholders of each company *per se*, premiums are associated with feed conversion and body weight produced (in comparison to the company's other growers) which provides incentive for growers to manage their flocks effectively. In

return, this improves quality control of the company and their resulting product. While each aspect of broiler production is undeniably important, many believe the most important aspect of commercial broiler production is associated with feed and feed manufacture due to the significant associated cost (60-70%).

Feed and Feed Manufacture

The evolution of the feed industry is one of historic proportions. While the exact date of the feed industry is unknown, it has been suggested that it began 12,000 years ago with the evolution of animal husbandry techniques during the era of the "Fertile Crescent" [9]. Through humble beginnings, the feed industry has continuously evolved allowing populations to continue to thrive and sustain life. While improvements have continuously evolved throughout time, it was during the 19th century when a more scientific approach began to take hold, yielding the more evolved feed industry that we utilize today [9]. In particular, the development of the "Proximate Analysis system" in 1860 by the Weende Experiment Station allowed quantitative values to be placed on ingredients providing for more precise diet formulation for the respective species [9]. Although the potential usefulness of this system for determining bioavailability is questioned, this system still is implemented in today's feed industry. Fourteen years later, Wolff began to establish a system for the determination of digestible coefficients for ingredients that provided a more precise understanding of ingredient bioavailability [10, 11]. This methodology was continuously improved with copious amounts of research in the following decades which led to the first nutrient requirements (NRC) being published in 1944; which is regularly updated and remains as a global standard for diet formulation of several animal species [9]. This history serves as the foundation for feed industry as

we know it today, and although manufacturing techniques have evolved, a similar process is still used today which will be discussed in further detail in the following sections with the major focus being on the poultry industry; specifically broilers.

Diet Formulation

The most critical step in ensuring a broiler achieves maximum growth potential is providing a diet that encompasses adequate proportions of each respective nutrient (i.e. carbohydrates, protein, lipids, vitamins, and minerals). These nutrients can come from ingredients present in the diet (i.e. corn, soybean meal, dietary fat/oil, etc.) or through the inclusion of additives (i.e. exogenous enzymes, crystalline amino acids, etc.). In the United States, the majority of diets are primarily composed (60-70%) of corn and soybean meal to help with meeting energy and protein requirements, respectively [12]. In addition to corn, dietary lipids, in the form of fat or oil, will be included in the diet to help ensure that the animal's energy requirements are met. Additions of other macro (meat and bone meal, limestone, and phosphate) and micro ingredients (trace minerals, vitamins, and crystalline amino acids) will be included in the remainder of the diet formulation to ensure growth and development is achieved. Additionally, the inclusion of exogenous enzymes is commonplace in today's poultry industry due to increased availability and knowledge of their mechanisms of action [13-16]. Utilizing these exogenous enzyme's increases the nutrient digestibility of ingredients present within the diet that results in improvements in broiler performance. While the concept of diet formulation is one that is relatively simple, implementation into the poultry industry can be rather cumbersome due to associated economics.

In today's poultry industry, utilizing "least-cost" diet formulation is the common practice. As the name implies, this system is one where the nutrient specifications must be adequately met to maintain performance at the lowest price in an effort to improve economic efficiencies and maximize profits. Due to the nature of ingredient prices not being static, this can result in differences in the ingredients and additives that may be "priced" into a diet formulation. Additionally, cost of transportation, seasonality, and availability may influence resulting ingredient prices limiting their nature into "least cost" formulation. This leads to concepts such as "opportunity values" and "shadow pricing" influencing the decision of when and how much a certain ingredient will be used. In particular, opportunity value is an associated value that one ingredient would have over another. For example, if crystalline amino acid could be obtained for a lower than typical price, this would result in a higher inclusion being called into a formula, allowing lower levels of protein sources, which are very costly, to be implemented, thus saving money. A similar concept is that of "shadow pricing". Traditionally, shadow values were thought of as two different values associated with nutrient constraints within the feed formulation and prices of ingredients [17]. However, Tahir and Pesti outlined the need to understand the relationships of these as they work in conjunction for practical diet formulation [18]. They outlined two different combinations they considered shadow values that included: 1) highest price at which the ingredient would be included in the solution or 2) lowest cost required for high cost ingredients to be able to be put into the formula. Utilizing these two factors, price curves were determined to outline the inclusion level of a particular ingredient into a diet formulation. It should be noted that the particular digestibility coefficient assigned to a particular ingredient drastically influences

the resulting shadow value and economics thus influencing the price curve. In particular, when comparing the similar ingredients using two digestibility databases, differences due to digestibility coefficients accounted for a potential savings of $160 million to the United States broiler industry associated with one database [18]. Although economics associated with "least-cost" diet formulation are of upmost importance in today's poultry industry, advancements in the understanding of broiler nutritional requirements can also lead to drastic improvements in broiler production.

While all areas of nutrition have improved, one of the most drastic improvements is understanding digestibility coefficients of respective nutrients. To determine the digestibility coefficients of nutrients, several assays have been developed. Of these assays, the most prevalent assays include the determination of apparent, true, and ileal digestibility. While these assays can be determined for any nutrient, perhaps one of the best examples is the determination of amino acid content of a respective diet/ingredient. It is important to note that in regards to protein requirements for avian species, it is truly a requirement for amino acids that is the determining factor for resulting performance [19]. Therefore, these aforementioned assays will be used for determination of each amino acid to be incorporated into diet formulations. Although a myriad of research exists regarding these assays and their individual differences [20- 24], they will not be discussed in further detail for this review. However, it is important to outline how these assays are critical for diet formulation and their importance in improving animal performance and reducing environmental impact from indigestible nutrients being excreted and applied to the land as fertilizer [25-27]. Determination of the respective digestibility coefficient to implement into the diet formulation falls solely on the nutritionist, but incorporation of

digestible fractions are common practice for all nutritionists. Once the diet formulation for each respective growth phase is completed, manufacture of the diets may begin. Feed manufacture happens in a series of steps that include grinding, mixing, and pelleting. Each of these steps will be discussed in further detail in the following sections.

Grinding

Following the receiving of ingredients, cereal grains (i.e. corn, wheat, barley, etc.) will often be ground to reduce particle size prior to mixing. Grinding is conducted due to previous research demonstrating the influence of ingredient particle size on broiler performance, nutrient adsorption, and gastrointestinal tract morphometry and development [28-31]. The process of grinding is two-step and includes the "disruption of outer seed coat and the exposure of endosperm" [30]. To perform the grinding of grains, a hammer-mill or roller-mill will be utilized dependent on the cereal grain being ground; with the utilization of a hammer-mill being more frequently implemented [32, 33]. Although particle size reduction for cereal grains is commonly performed at the respective feed mill, many ingredients will not have further modification upon receiving prior to mixing. This is particularly important for protein meals, specifically soybean meal, which will be implemented as the major protein source in a typical broiler diet. Even though the general concern with soybean meal processors is proper heat treatment to deactivate trypsin inhibitors, which would decrease protein digestibility [34-37], they should remain cognizant of particle size due to previous research demonstrating differences in broiler performance as a result of differences in soybean meal particle size [38].

Although reduction in particle size of cereal grains is essential to improve broiler performance, the resulting economics associated with the grinding of grains is one of important consideration. In particular, it has been well established that energy costs associated with a hammermill may be influenced by a variety of factors such as fiber content, moisture of grains, screen size, hammer tip speed, condition of hammers, and feeding method; among several others [39-43]. Therefore, it is hard to put a specific dollar amount on the cost associated with the grinding of feeds. However, one commercial manufacturer has estimated that the cost associated with grinding of corn using a hammermill ranged from $0.15 to $0.25 per ton [44]. Due to the production of high feed volumes associated with each individual commercial feed mill, this cost is cumulative and is one of important consideration. While aforementioned performance benefits necessitate the use of reduction in particle sizes, perhaps one of the most important factors to consider is the improvement in the homogeneity of diet formulations associated with mixing due to particle size reductions.

Mixing

Proper mixing of the respective diet formulation is of utmost importance to prevent potential segregation of ingredients that may negatively affect performance [45, 46]. To perform mixing, a variety of mixer configurations may be utilized which include ribbon mixers, paddle mixers, twin-shaft mixers, and drum mixers. While each mixer configuration has pros and cons associated with the design and implementation, their basic function is similar. Typically, dry ingredients will be mixed prior to liquid ingredient inclusions. The length of mixing time following the addition of each ingredient

will differ based on the respective feed mill and batching/mixing system they are implementing.

Although the process of mixing is one that is intuitive, the importance of a proper mix cannot be overstated. Beumer suggested that mixer uniformity is one of the most important aspects in feed manufacture [45]. McCoy and cohorts evaluated the effects of differences in mixer uniformities due to time and determined improvements in BW gain, feed intake, feed conversion ratio (FCR) and decreased mortality as the time of mixing was increased [46]. These improvements in performance due to increased uniformity also help alleviate concerns with nutrient safety margins [47] while meeting regulatory aspects [48]. To ensure diets are properly mixed, determination of the mixer CV following different mixing times is performed. Representative samples (~10) will be collected and a selected nutrient indicator will be analyzed to determine concentrations for each sample, and CV will be determined using the following equation: % CV= ((Standard Deviation of Samples/ Sample Mean) x 100) [49]. Several nutrient indicators may be used to determine mixer CV, with the most prevalent being sodium chloride. However, it is important when selecting a nutrient indicator to ensure the following criteria are met: 1) specificity to one ingredient, 2) assay is accurate and precise for the inclusion level, 3) assay is not cost prohibitive, and 4) inclusion level in the sample is large enough for statistical approximation of a normal distribution [49]. A CV of less than 10% has traditionally been accepted as being adequate; with a CV of lower than 5 % being ideal.

While the traditional method of testing mixer CV has been practiced extensively, processes following the mixing process, such as pelleting, cooling, augering, and

transportation, may influence segregation of the diets making the mixer less than ideal to confirm diet formulations and homogenous mixtures. Additionally, obtaining samples from the mixer may be infeasible dependent on the mill's schematics. One study of interest looked at the influences of mixing time (30 s vs 10 min), sampling location (post-extrusion or cooled pellets), number of samples (2 vs 10), and sample blending techniques (hand mixed hand or using sample splitter) using DL-Methionine as the nutrient indicator [50]. Although findings for several of these main effects were present, perhaps the most important finding from this work demonstrated that samples collected from the pellet die (post-extrusion) provided the best metric for validating the intended diet formulation.

Regardless of method used to validate diet formulations, it is imperative to ensure that intended diet formulation is being delivered to the broilers to ensure performance objectives are being met. Mixers have been used extensively to help ensure diet formulations are homogenous in nature. Traditionally, determining the mixer CV routinely will help to guarantee that a homogenous mixture is being created prior to the pelleting process. Once the desired mixing time has been validated for each respective feed mill, this will become a standard procedure for mixing all diet formulations.

Pelleting

The process of pelleting has been defined as the "agglomeration of small particles into larger particle by the means of a mechanical process in combination with moisture, heat, and pressure" [51]. Following the mixing process, unconditioned mash will be transferred to the surge bin of the pellet mill for the pelleting process to begin. The first step in the pelleting process is conditioning, in which saturated steam (~95% water

vapor) will be incorporated into mash through steam ports located on the conditioning barrel. Incorporating saturated steam at high conditioning temperatures is beneficial for pellet formation as these conditions are conducive for starch gelatinization and protein gelation to occur [52, 53]. Although research on the extent of starch gelatinization in pellet durability is debated, it is generally conceived to be beneficial for the creation of pellets and their resulting durability [53-57]. Moreover, Briggs and cohorts suggested that protein gelation had the biggest impact on pellet formation and resulting pellet quality [52]; with subsequent research confirming higher protein rations improved resulting pellet quality [58, 59].

Following the conditioning process, pellets will be directed to the pellet die chamber via a feeder cone. In this chamber, feed will be extruded through the pellet die by corrugated rolls, which subjects feed subject to the following forces: roll force, die force, and slip resistant force. Following extrusion, pellets will be cut to a desired length using sets of knives that are affixed around the pellet die. Hot pellets will be then be directed to a cooler to remove moisture and lower temperature in an effort to increase structural integrity and inhibition of mold due to moisture. Although several types of coolers (vertical, horizontal, and counter-flow) are prevalent in today's feed industry, the main objective is similar for all configurations. Even though the process is a relatively simple concept, important considerations must be accounted for to ensure proper cooling. Of these, two of considerable importance are resulting bed depth and retention time in the cooler [60]. Due to the nature of air taking the path of least resistance, bed depths that are not uniform will result in high spots of pellets resulting in less temperature reduction and moisture removal [61]. Additionally, if pellets are not retained for the proper length of

time, proper cooling will not be achieved. The pellet is in a state of unnatural balance, with the center of the pellet having the highest percentage of moisture [60]. During the cooling process, this moisture will migrate to the outside diameter of the pellet allowing the ambient air to remove this moisture and temperature. However, this process will not occur correctly if the production rate of the pellet mill is not properly matched to the retention rate of the cooler. This retention rate may also need to be adjusted in systems with variable drives based on the diameter of the pellets; with large diameter pellets needing larger bed depths and retention time.

Following the cooling of pellets, particle size of the whole diet may be reduced by the utilization of a crumbler; which utilizes a similar grinding method as that of a roller mill. Typically, diets fed in the early stages of a broilers life (i.e. starter phase) are crumbled to ensure that prehension of feed may occur. In diets that will be fed solely as pellets, the crumbler will be bypassed and the pelleted diet will be directly sent to the storage bin. This outline provides a general overview of the feed and feed manufacture process; which may vary based on the respective feed milling operation. However, the major focus for this literature review will be outlining previous research examining the effects of feed form (FF) on broiler performance due to the associated economic implications for a commercial poultry operation.

Effects of Pelleting on Broiler Performance

Utilization of a pellet mill in the United States for animal feed was first introduced in the 1920's by Purina [9]. The underlying objective for this process was the conversion of bulky, fibrous, and often unpalatable materials into a pellet to facilitate prehension [9, 62]. While technological advances in feed manufacturing are easily

apparent [11, 63], the pelleting process utilized today is similar to that of five decades ago [64]. Today's broiler is fed a diet exclusively comprised of pellets due to associated improvements in broiler performance [28, 55, 65-72]. Several underlying factors support the incorporation of pelleting in a commercial operation. These categories fall into two distinct categories that are improved feed efficiencies and handling characteristics [60].

It has been well established that pelleting of feed improves FCR and BW gain compared to broilers receiving an unconditioned mash diet [65, 68, 73-76]. While data is conflicting, pelleting of diets does not appear to improve feed efficiency by increasing the digestibility of nutrients [77], but rather the induction of increasing feed intake [77-80]. Due to the increased improvements in FF, prehension energy is reduced allowing more energy to directed to productive responses [81, 82]. This increase in productive energy may be associated with increased time resting for broilers receiving pelleted diets. One of the first studies to demonstrate this effect was conducted in 1963 and demonstrated broilers spent ~14% of their time actively eating during a 12 hour feeding period when presented mash in comparison to only 5% when given pelleted diets [65]. McKinney and Teeter demonstrated a similar effect with an increase in resting time for broilers when given diets of a higher pellet quality; even though differences in feed intake were not apparent [81]. Moreover, recent research has also demonstrated that genetic strain plays a role in the behavioral aspects when coupled with pellet quality [83, 84]. Although genetics have changed drastically from 1962; in general, it appears that creation of high quality pellets results in improvements in prehension energy.

In addition to improvements in feed intake, increased feed efficiencies associated with decreased ingredient segregation have been attributed to the pelleting of diets. Due

to mechanoreceptors located in the beak of broilers, birds will often select particle sizes based on beak capacity [85, 86]. Schiffman demonstrated broilers had a preference for a larger particle size [87], while other works have demonstrated that this preference will increase as broilers age [88-90]. The process of pelleting results in a more homogenous particle size (*per se*), preventing feed wastage as a result of birds actively searching and selecting desired particle sizes [91]. Moreover, this helps to ensure that broilers consume the formulated diet in its entirety, rather than selecting singular ingredients with an associated particle size which would result in nutritional deficiencies [51, 92].

Although commercial integrators are well aware of broiler performance improvements beginning associated with pellets of high quality, integrators are often hesitant to invest in the production of high quality pellets. It has been outlined that this hesitation is associated with feed manufacturing equipment/throughput constraints, as well as keeping up with advancements in other areas of production (i.e. genetics and nutrition) [93]. It has been suggested that the investment in pellet quality should be recovered in integrated systems; often resulting in higher economic profits [94]. However, it should be noted that this has often been a subject of disagreement between researchers and integrators due to the relationship between animal performance and cost efficiency [95]. This is primarily due to the belief that the additional investment to improve pellet quality will not result in recovery of the investment due to the inability to create pellets at high enough quality [96]. Moreover, feed manufacturing techniques that are employed to improve pellet quality at the feed mill are likely not indicative of the percentage of pellets broilers would receive at the feed pan due to the deleterious effects of transportation and augering [66, 97, 98]. One underlying issue complicating the

decision on investing in pellet quality is the amount of research is limited; making informed decisions rather difficult.

In regards to pellet quality, Reimer outlined five factors, and respective percentages that influenced resulting pellet quality [99]. These factors and respective percentages were diet formulation (40%), particle size of ingredients (20%), conditioning (20%), die specifications (15%), and cooling and drying (5%). In addition to these five factors, Behnke outlined that throughput should be considered as contributor to resulting pellet quality [75]. With these factors in mind, research has provided several intuitive strategies to improve pellet quality. These include lowering production rate [58, 69], reducing corn particle size [100, 101, incorporating a thicker pellet die [58, 102] increasing conditioning temperature [69, 103], utilizing a pellet binder [58, 59, 102, 104-106] and manipulating diet formulation [52, 58, 69, 105, 107]. Although these strategies provide a framework to improve pellet quality, it is imperative that one remembers that the six factors outlined by Reimer and Behnke not only impact pellet quality, but also nutrient availability [75, 99]. Due to the interactive effects of these factors on pellet quality and nutrient availability, which work in combination to influence resulting broiler performance, research should hold one of these constraints (i.e. pellet quality or nutrient availability) constant to prevent confounding results [59, 69, 108-111]. With this ideology in mind, collaborative efforts between Mississippi State University and West Virginia University have been conducted to determine the effects of FF on broiler performance. In addition to these collaborative efforts, work as Massey University by scientists Abdollahi and Ravindran looked at the effects of pellet diameter and lengths of

common diets. The importance of these studies to our proposed work in the following chapters will be discussed in further detail in the following section.

The Effects of Feed Form on Broiler Performance

One of the fundamental papers utilizing this ideology was conducted by Lilly and coauthors at West Virginia University [69]. This paper conducted two experiments to determine the effects of FF on finishing [d 21-42 (Experiment 1) or d 21 -38 (Experiment 2)] Cobb 500 broiler performance. In the first experiment, different manufacturing techniques (e.g. conditioning temperature, die thickness, and production rate) were implemented during the finisher period to create diets of differing pellet durability indexes (PDI) ranging from 71 to 96%. Birds were fed a common diet during the starter period [mash (d 0-7) and fine crumbles (d 7-21)] and then presented five different FF during the finisher phase. Differences in BW gain and FCR were not apparent for any of the FF presented. This finding was counterintuitive, as one would believe that performance differences would be apparent as PDI increased. The authors of this paper attributed this to two possible scenarios: pellet quality was not important during the grower phase or the experiment was confounded due to changes in nutrient availability; with the latter being speculated as the causative agent. This experiment demonstrates the importance of maintaining nutrient availability to determine the true effects of FF on broiler performance.

This work led to the second experiment in which a similar methodology was implemented, with the exception of utilizing similar manufacturing techniques to prevent confounding effects of nutrient availability. One common diet was created using manufacturing techniques (e.g. slow production rate, “thick” pellet die, high steam

pressure and conditioning temperatures) that would support the creation of high quality pellets (i.e. 90% pellets). A portion of this diet was collected and ground via roller mill to for the creation of "fines". A stepwise gradient of increasing intact pellet percentages (e.g. 30% Pellets and 60% Pellets) was created by hand mixing "fines" in appropriate proportions to the original pelleted diet. Additionally, one treatment comprised entirely of ground pellets ("fines", 0% pellets) was fed for a total of four dietary treatments that differed only in FF. Conversely to experiment 1, improvements in BW gain as percentage of pellets increased were apparent; with the highest performance benefit being associated with 90% Pellets. However, it is important to note that improvements were not apparent in FCR for the three different pellet percentages (i.e. 30, 60, or 90%), with treatments performing similar among one another and greater than broilers receiving 0% Pellets. An interesting aspect from this work was the utilization of an economic model with observed performance and processing characteristics in an effort to determine relative cost savings. With feed cost set at $330/tonne, a cost savings of $0.05/kg of carcass weight was demonstrated for broilers receiving diets comprised of 90% pellets. However, producing pellets of this high percentage is likely infeasible for a commercial feed mill. Thus, future research examined the effects of a more modest improvement in pellet quality to determine the effects on broiler performance.

One such study was conducted by Lemons and Moritz at West Virginia University [70]. This study employed a 2 x 2 factorial arrangement between the main effects of feeder space access and FF. For the purpose of this summarization, only the impacts of the main effect of FF will be discussed. In each of three growth phases, high or low FF was provided as crumbles (starter and grower) and pellets during the finisher

growth phase. In regards to crumbled treatments, crumbles of 1191 or 951 µm and 2133 or 1096 µm in the starter and grower phases were fed, respectively. During the finisher phase, broilers received 70% or 40% pellets; with the 40% diet being created in a similar methodology as described for Lilly and cohorts [69]. During the starter phase (d 0-10), only FCR was affected with Hubbard x Cobb 500 broilers receiving 1191 µm crumbles resulting in a 0.055 improvement in comparison to those receiving 951 µm. However, in the grower (d 11-22) and finisher (d 23-38) growth phases, BW gain was also improved along with FCR for broilers receiving high FF (2133 µm or 70% Pellets, respectively). Broilers receiving 2133 µm crumbles in the grower phase resulted in a 31 g improvement in BW gain while improving FCR 0.035. Additionally, broilers receiving 70% pellets during the finisher growth phase improved BW gain by 66 g with an improvement in FCR of 0.053. When examining overall data (d 1-38), providing high FF resulted in 102 g improvement in BW gain while reducing FCR 0.026.

In similar a manner, Glover and cohorts examined the effects of feeding two FF qualities, “standard” or “improved”, in three dietary phases on Hubbard x Cobb 500 broiler performance [71]. Average particle size was not provided for crumbles in the starter (d 1-10) and grower (11-21) dietary phases. However, a stack of American Society of Agricultural Engineers #6 and #14 sieves was used to provide descriptive data of particle size distribution for the standard and improved FF. Feed retained on the #6 sieve was classified as a pellet whereas feed retained on the #14 sieve was considered crumbles; unretained feed was classified as fines. Feeding “improved” crumbles (71% crumbles) during the starter period resulted in a 0.02 improvement in FCR compared to “standard” crumbles (51% crumbles) However, feeding “standard” crumbles during this

period resulted in a 5 g BW gain improvement compared to those fed “improved” crumbles. Performance differences attributed to FF were not apparent for any metric in the grower phase. During the finisher phase (d 22-38), broilers receiving improved FF (69% pellets) resulted in a 0.06 FCR improvement compared to those receiving standard FF (54% pellets). Although FCR improvements were established for FCR in the starter and finisher growth phases, improvements in overall (d1-38) FCR due to FF were not apparent.

These works of Lemons and Moritz [70] and Glover and cohorts [71] demonstrated that modest improvements in FF may improve broiler performance; with improvements in FCR being more apparent. However, only one strain (i.e Hubbard x Cobb 500) was implemented in both studies, making results not necessarily applicable to broilers of other commercial strains. One such study that accounted for genetic strain and FF was conducted by Sellers and cohorts at Mississippi State University [72]. In this trial, two commonly implemented genetic strains, labeled fast-growing and high-yield, were fed modest improvements in FF using an incremental system similar to that of Lilly and coauthors [69]. Broilers of both genetic strains were fed 50, 60, 70 or 80% pellets of a nutritionally common diet from d 28-42 to determine the effects on broiler performance and d 43 processing characteristics. Examining the effects of FF, birds fed 80% pellets resulted in 0.08 and 74 g improvement in FCR and ending BW compared to those fed 50% pellets, respectively; 60 and 70% pellets performed intermediate. Similar to previous work, improvements in FF resulted in increased broiler performance, with this study demonstrating a similar response for two genetic strains. One interesting finding from this study was the improvement of approximately 0.03 improvement in FCR for

each 10% increase in percent pellets, which was greater than previous works demonstrating a 0.004 improvement in FCR for each 10% increase in pellets [69].

Although it has previously been outlined that the effects of FF and nutrient availability interact to collective influence broiler performance, few studies differentiate these effects making holistic recommendations to the commercial industry rather difficult due to potential for confounded results. To our knowledge, the only other studies to differentiate these effects, similar to that of previously discussed works, were conducted by Abdollahi and cohorts at Massey University. In this series of four experiments, the influence of pellet diameter and length was examined to determine the effects on broiler performance using both corn and wheat based diets. Looking at the effects of corn based diets [112], one study was conducted utilizing a 2 x 2 factorial arrangement with the main effects being pellet diameter (3 or 4.76 mm) and pellet length (3 or 6mm). Male broilers of the Ross 308 genetic strain were provided common diets during the starter growth phase (d 0-9) followed by experimental diets during the grower (d 10-21) and finisher growth phases (d 22-42). Regarding performance, the only performance benefit established for the entirety of the study was associated with pellet diameter during the grower growth phase. Broilers receiving 3 mm diameter pellets resulted in a FCR improvement of 0.02 compared to those receiving 4.76 mm diameter pellets. However, this performance benefit was diminished for overall performance warranting future research examining the effects of pellet diameter and length in wheat based diets.

Looking at the effects in wheat based diets, three studies were conducted utilizing different pellet lengths, pellet diameter, or a combination of both. The first of these experiments replicated the treatment structure of that described previously for the corn

based trial; with the only exception being the main cereal grain source. During the grower period (d 10-21), broilers receiving pellets with a length of 6 mm demonstrated an improvement of 20 g and 0.02 in BW gain and FCR when compared to those receiving pellets of 3 mm in length, respectively [113]. For the finisher (d 22-42) and overall experimental period (d 10-42), the main effects of pellet diameter and length interacted to influence FCR, without apparent benefits for BW gain. For these interactions, pellets of 3 mm diameter performed similar for both lengths; whereas increasing the length for 4.76 mm diameter pellets resulted in reductions in FCR. Due to the main effect of length impacting grower phase performance and interactions during the finisher and overall performance affecting broiler performance in all growth phases, the impact of pellet length on starter performance (d 7-21) in wheat diets was further investigated.

This study looked at the impacts of pellet length (3, 5, or 7 mm) on Ross 308 male broiler starter performance (d 7-21) [114]. Broilers were presented common starter diets, 3 mm in length, from d 0-6, and five combinations of differing pellet lengths were given during the experimental period (d 7-21). These five combinations were presented with adaptions during the second (d 7-14) and third weeks (d 15-21) following the common starter diet. For these combinations, three treatments received 3 mm from d 7-14 with the other two combinations receiving 5 mm during this day range. For the third week (d 15-21), the combinations receiving 3 mm from d 7-14 received 3, 5, or 7 mm pellets, whereas the two combinations receiving 5 mm pellets from d 7-14 received either 5 or 7 mm for the creation of five distinct treatments. For the entire starter period (d 7-21), broilers receiving pellets of 3 mm in length resulted in the highest BWG; with only

treatments receiving 5 and 7 mm from d 7-14 and d 15-21, respectively, performing similar.

Utilizing aspects of all the aforementioned trials, the final study was performed to determine the effects of pellet diameter and length of finisher diets on finishing performance (d 22-42) of Ross 308 male broilers [115]. During this trial, pellets were offered as 3 or 4.76 mm in diameter and lengths of 7 or 9 mm. Similar to the starter study, adaptions containing different schemes of when a respective pellet length and diameter would be presented (d 22-28, d 29-35 and d 36-42) were implemented to create a total of eight different treatment adaptations. Interactions between pellet length and diameter, as well as the main effect of pellet length, were not apparent for any of the periods. However, pellet diameter influenced d 29-35 BW gain and FCR resulting in an 83 g and 0.12 improvement, respectively, for broilers receiving pellets of 3 mm diameter. This translated to an overall (d 22-42) improvement of 129 g and 0.06 for BW gain and FCR, respectively.

These experiments demonstrate that modest improvements in FF result in improved broiler performance. However, results are not conclusive on the effects of FF for each desired performance metric (i.e. BW gain and FCR). This makes providing holistic recommendations to commercial integrators rather difficult. Although a general trend for improvements in broiler performance due to FF are elucidated, it appears that the relationship is rather complex and influenced by a variety of factors. The current research in the following chapters aims to help address several of these factors, which will be described in the following section.

Factors Influencing Broiler Performance due to Feed Form

Growth Phase

Many of the previous works described primarily focused on the finishing growth phase, as this phase is associated with the highest feed consumption. Due to the high feed consumption associated with this growth phase, it has been presumed that this would result in the greatest opportunity to observe performance benefits due to FF. While this is intuitively true, research examining the influences of FF presented in each phase of a growout, as well as the potential for FF to interact, is particularly void in previous literature. Choi and cohorts demonstrated numerically improved BW gain for broilers receiving pelleted diets during the finisher growth phase (d 28-56) after previously receiving unconditioned mash in the starter phase (d 1-28) [74]. This finding was interesting as broilers receiving unconditioned mash resulted in lowest BW gain during the starter phase. This was the first experiment, to our knowledge, to demonstrate the potential for FF presented in each dietary phase to interact. More recently, a similar response was demonstrated for broilers receiving mash from (d 1-21) having an improved d 21-42 FCR, compared to those previously receiving crumbles or pellets in the starter phase [116].

Although these findings are somewhat counterintuitive, it is likely the adaption between FF presented in each growth phase influenced these results. One such study demonstrated that FF presented in the grower (d 23-36) and finisher (d 37-44) growth phase interacted to influence feed intake. Broilers presented the other FF (i.e. mash or pellets) resulted in a higher feed consumption in comparison to those remaining on the same FF in both growth phases [83]. These findings may have been influenced by

genotype, as studies comparing FF adaptations in fast and slow growing genotypes demonstrated broilers of fast-growing genotypes were extremely sensitive to any modifications in FF, with respect to percentages of fines and pellets [117]. Moreover, these adaptations in fast-growing genotypes were short in time (<10 min), with these behavioral adaptations remaining longer in comparison to those of the slow-growing genotypes.

While these findings demonstrate the potential for FF to interact in each growth phase, this relationship is not thoroughly understood. Due to the nature of the poultry industry and feed delivery schemes, the FF presented throughout a commercial grow out can vary immensely. Therefore, understanding the impacts and interactions of FF presented in each growth phase will be instrumental in providing holistic recommendations to commercial integrators (Chapter 2). Additionally, understanding the effects of FF presented during the earlier stages (i.e. starter) of the commercial grow out is lacking and will be the major focus of this dissertation (Chapters 3 and 4).

Starter Phase

The starter phase (<14 d) represents a critical stage in a broiler's lifecycle. Due to the decreased time required for reaching targeted markets, the first days following hatch represent a significant percentage of a broiler's life span [64]. During the starter phase, the gastrointestinal tract, particularly the small intestine, is forming at a tremendous rate [118]. This makes formation of the gastrointestinal tract during the starter phase critical for improvements in digestion to maximize performance [119, 120]. Due to the fact that digestive enzyme efficacy is limited during early stages of a broiler's life, this creates a major concern surrounding the digestion and absorption of nutrients [121]. Therefore, it

is critical to ensure that feed intake occurs as quickly as possible to facilitate nutrient assimilation/digestion [64]. To facilitate apprehension of feed, common practice has been to crumble feed for reduction in particle size. Although this is common practice in the commercial industry, few studies have been conducted with the main objective to determine impacts of crumble particle size on broiler starter performance.

Works by Cerrate and cohorts looked at the impacts of improved FF by providing micropellets or crumbles, compared to unconditioned mash, on Cobb 500 male prestarter (d 0-7) and starter (d 0-13) broiler performance [122, 123]. These studies demonstrated that BW gain and FCR was improved when higher quality FF (i.e. micropellets or crumbles) were provided in comparison to unconditioned mash. Additionally, Lemons and Moritz demonstrated improvements in d 0-10 FCR for Hubbard x Cobb 500 broilers when providing 1191 µm in comparison to 951 µm crumbles; without apparent benefits in BW gain [70]. Glover and cohorts also demonstrated improvements in d 0-10 FCR for Hubbard x Cobb 500 broilers when providing "improved" crumbles [71]. However, BW gain was improved for broilers receiving standard crumbles in this trial. These studies demonstrate the potential for crumble particle size of nutritionally common diets to influence broiler starter performance. However, making a recommendation for the optimal crumble particle size to feed during the starter growth phase is difficult, due to differences in genetic strains implemented and failure to adequately describe the average particle size and distributions of the treatments provided.

Determining the optimal particle size could have serious economic implications for the commercial industry due to improvements in starter broiler performance and feed mill efficiencies. Abdollahi and Ravindran outlined the need to determine the appropriate

pellet size (length and diameter) for each growth phase to improve broiler performance [114]. As previously discussed, broiler chickens have mechanoreceptors in their beaks which are able to detect particle sizes of feed/ingredients. These mechanoreceptors play any extremely important role in the starter growth phase since feed is ground to a desired particle size, which will influence broiler chick acceptance or rejection of the feed. One such study examining the biomechanics of broiler chicks demonstrated that two-thirds of pecks do not result in the apprehension of feed particles [124]. Other works have examined the feed preference of broiler chickens when given a variety of different feed particle sizes. Huang and De Beer demonstrated that broiler chicks (unspecified genetic strain) demonstrated preferences for crumble particle size, with the preference for a larger particle size as broilers increased with age [125]. However, the most important finding from this work was that birds would reject fine particles (< 860 µm) as early as 3 days post-hatch. Moreover, broiler performance was improved when broilers were presented their preferred crumble particle size (2180-3180 µm) at d 9 of age.

These data demonstrate the inherent need to identify the optimal crumble particle size for improvements in broiler starter performance. Although, commercial integrators remain cognizant of this, many do not implement quantitative measures to ensure a desired particle size is being presented (based on personal conversations of the author with feed mill managers). The major concern for many integrators is creating a crumble of small particle size to ensure consumption and prevent presumed recalls and/or feed wastage that may be associated with providing a crumble of a large particle size. However, due to rapid improvements in genetics, broiler chickens may be able to consume particles much larger than originally anticipated. Furthermore, due to the lower

feed volumes associated with starter feed, in comparison with volumes required for the finishing growth phase, potential improvements in overall performance and processing characteristics due to starter FF may justify the additional investment. Moreover, if larger crumble particle size may be fed, this would reduce the associated energy consumption associated with the crumbler resulting in improved feed mill efficiencies and resulting profits.

Genetic Strain

All facets of broiler production have made tremendous strides to result in the commercial poultry industry we know today. However, it is hard to argue that the most tremendous improvement in today's industry is not associated with improvements in the genetic potential of today's broiler [126-129]. Due to these monumental improvements in genetics, nutritional requirements have also dramatically changed [130]. Therefore, the opportunity for broiler performance to be maximized with different FF, specifically crumble particle size, is present.

One such study that looked at the effects of FF in differing genetic strains was conducted by Sellers and cohorts [72]. Although these main effects of FF and genetic strain did not interact to influence d 28-42 broiler performance (previously discussed), interactions for breast yield were apparent. Broilers of a fast-growing genetic strain demonstrated an improved breast yield, compared to those of a high-yielding genetic strain, when provided 50, 60, or 70% pellets of a common diet. However, both strains demonstrated similar breast yield when provided 80% pellets which led to the conclusion that high-yielding broilers may be more sensitive to changes in FF compared to those of a fast-growing variety. In an effort to follow up to these findings, Chapter 4 will employ

the same genetic strains to determine the effect of starter FF and feed quality on starter and overall performance and processing characteristics.

Gastrointestinal Tract Development

The impacts of ingredient particle size on gastrointestinal morphology and development have been extensively studied in past research. Of this research, the majority of these effects were demonstrated for gizzard development. Nir and cohorts demonstrated that broilers receiving "medium" or "coarse" particle size diets demonstrated an improvement in gizzard development and reduction in gizzard pH [28]. Moreover, studies have demonstrated that fine grinding of cereal grains, often incorporated to improve PDI or nutrient utilization, results in gizzards that are underdeveloped and function more as a transit organ; rather than intended function of grinding [131, 132]. Although particle size of ingredients have demonstrated effects on gastrointestinal tract development, the influence of ingredient particle size has been considered to be less critical in processed feeds due to research demonstrating similar effects when diets are pelleted or crumbled [30]. Moreover, the effects of the particle size of a complete diet on gastrointestinal development is not present in current literature; especially in diets that differ only in FF.

Certain works have demonstrated reductions in small intestine and gizzard weights when associated with birds receiving pelleted diets in comparison to those being fed mash [133, 134]. Looking at the effects of diets differing in FF, Adbollahi and cohorts demonstrated reduction in gizzard weights for corn based diets when pellet length was increased from 3 to 6 mm for 3 mm diameter pellets; without observed differences for pellets of 4.76 mm diameter [112]. In a similar study utilizing wheat based diets,

increasing pellet diameter and length resulted in shorter lengths of the duodenum [113]. Additionally, ileum length has been reduced when feeding pelleted diets in comparison to birds receiving mash diets [135]. Similarly to these findings, Naderinejad and cohorts demonstrated reduced lengths for all sections of the small intestine associated with pelleting; as well as reduced pancreas, proventriculus, and gizzard weights [136].

These studies demonstrate that FF can influence gastrointestinal development and morphology. In general, it appears that particle size and FF directly influences gizzard weights and small intestine lengths. However, these aforementioned studies solely focus on comparing pelleted diets to unconditioned mash, which lends itself to confounded results. Due to the general knowledge that particle size is more influential on mash diets when compared to pelleted diets, these provide little insight on how particle size of complete diets will influence gastrointestinal development. With this in mind, Chapters 3 and 4 performed gastrointestinal sampling to help provide a mechanism of action associated with expected performance benefits due to starter crumble particle size.

Conclusions

The poultry industry as we know it today is a result of tremendous scientific efforts performed in the past decades. These improvements have resulted in an extremely stable industry that will help to feed the ever-increasing world population. Although all segments of the poultry industry are vital to its success, it may be argued that feed and feed manufacture are of high importance due to their substantial investment to the total cost of production. Within the feed and feed manufacture segment, research pertaining to FF is extremely important due to additional investment to improve FF.

Today's broiler is fed an exclusively pelleted diet due to associated improvements in broiler performance and resulting economic efficiencies. These improvements are further elucidated when higher quality FF is presented. Although commercial integrators remain cognizant of this fact, hesitation remains due to the belief that the additional investment to improve FF will not be recovered. One underlying issue for this hesitation is the limited scientific evidence on which to base strategies for their respective operation. In addition to the limited research, research is often confounded due to methodologies that influence nutrient availability and FF, which collectively influence resulting broiler performance.

Collaborative efforts at Mississippi State University and West Virginia University have adapted this ideology to provide more information on the impacts of FF on broiler performance in an effort to make a holistic recommendation for commercial integrators. However, the majority of this research has primarily focused on the finishing growth phases. The aim of this dissertation is to provide valuable insight on the effects of FF in earlier growth phases (i.e. starter) on broiler performance. Due to the lower feed volumes associated with this growth phase, this research has the opportunity to significantly impact the commercial industry if improvements associated with starter FF result in benefits for overall broiler performance and processing characteristics.

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CHAPTER II

INTERACTIVE EFFECTS OF HIGH OR LOW FEED FORM AND PHASE OF FEEDING ON PERFORMANCE OF ROSS X ROSS 708 MALE BROILERS THROUGHOUT A 46 D GROWOUT

Summary

Previous research has focused on providing improved feed form (FF) in the finishing growth phase of broilers (>28 d) to optimize performance. However, it may be more economical to improve FF in earlier growth phases (<28 d), when less feed volume is required. Therefore, the current study utilized a 2 x 2 x 2 factorial arrangement of treatments within a randomized complete block design using two FF presented in each of three growth phases. In the starter growth phase (0-14 d), broilers were provided either of two FF, ground crumbles (988 µm) or crumbles (1785 µm). This was followed with the grower phase (14-28 d) where broilers were given either of two FF, 50 or 80% intact pellets (IP). Lastly, in the finisher phase (28-46 d) birds were provided either 50 or 80% IP. Broilers receiving crumbles and 80% IP had increased feed intake and body weight (BW) in the starter and grower growth phases. Providing broilers crumbles decreased FCR by 0.02 in the starter growth phase. Feed form in the starter and finisher growth phases interacted for d 46 BW, demonstrating birds fed ground crumbles (starter phase) and 80% IP (finisher phase) resulted in the highest BW. However, feeding crumbles in the starter phase and 50% IP in the finisher phase resulted in similar BW improvements.

These data suggest that broilers may compensate for reduced BW from receiving ground crumbles in the starter phase by receiving higher quality FF (i.e. 80% IP) in the finisher phase.

Description of the Problem

Significant costs associated with feed and feed manufacture have been well recognized throughout the commercial poultry industry. However, costs may be justified through improved performance associated with pelleting. Previous literature has consistently demonstrated improvements in broiler performance as a result of receiving a pelleted diet, with increases in FF quality resulting in greater performance benefits [1-11].

Feed form has often been the subject of discussion between researchers and feed manufacturers due to concerns of improved animal performance versus associated economics [12]. While it has been suggested that improved FCR should cover this investment for integrated systems [13], the additional investment of time and energy associated with producing high FF has often resulted in hesitation in the commercial industry. Additionally, previous literature has suggested that benefits of providing high FF may be difficult to fully appreciate, as techniques utilized to improve FF may have deleterious effects on nutrient availability [8, 9, 14-18]. Therefore, the effects of FF and nutrient availability should be separated in research studies to fully appreciate improvements in broiler performance as a result of receiving higher quality FF.

One such paper that utilized this ideology was conducted at West Virginia University in 2011 by Lilly and cohorts [9]. These authors utilized increased ratios of IP: ground pellets ("fines"; 0:100, 30:70, 60:40, and 90:10). All diets were created by

grinding a portion of the 90:10 diet using a roller mill to create "fines" and hand mixing to the desired ratio in an effort to maintain nutrient availability. This study demonstrated that 21-38 d Cobb 500 broiler performance was improved as percent of IP increased; with 90% IP resulting in the greatest performance improvement. Utilizing an economic model (feed cost set at $330/tonne), these authors established a $0.05/kg savings relative to carcass weight associated with feeding 90% IP. However, 90% IP may not be feasible for commercial mills to attain. This encouraged more recent research to examine the benefits of modest improvements in pellet quality that would be more easily obtainable in commercial production. A table briefly summarizing the significance of their work can be located in Table 2.1. These studies verified that modest improvements in FF can improve broiler performance. However, these studies also primarily focused on the finishing growth phases, due to the high feed consumption and thus the greatest potential to observe performance benefits associated with high FF.

Due to the investment required to produce high FF, it may be more economical for poultry producers to improve FF in the starter and/or grower phases due to the lower feed volume demand. Previous research with focus on the starter growth phase did not separate confounding effects of comparing processed feed to unconditioned mash, but improvements were still established for high FF [19, 20]. However, these improvements were diminished at market weight and speculated to be due to compensatory growth. Similarly, Choi and others demonstrated improvements in starter performance (< 28 d) when feeding a crumbled diet versus an unconditioned mash [21]. However, FF presented in the starter (0-28 d) and finisher (28-56 d) growth phases tended to interactively affect BW gain; with 0-56 d BW gain being maximized when broilers were fed unconditioned

mash during the starter phase and a pelleted diet in the finisher phase. These data were to our knowledge the first to demonstrate that FF manipulations interact with phase feeding to affect overall broiler performance. However, this study was published in 1986, therefore the strain utilized would drastically differ from today's commercial broilers strains.

Due to improvements in broiler genetic potential, it is important to explore the possibility of interactions between FF presented during each growth phase. Additionally, improvements in broiler performance associated with improved FF during the early growth phases may translate to improved overall performance, providing potential economic implications. Therefore, the objective of the current study was to assess the interaction of low or high feed form and phase of feeding on broiler performance.

Materials and Methods

Experimental Design

The current experiment utilized a 2 x 2 x 2 factorial arrangement within a randomized complete block design. The main effects consisted of three growth phases that utilized either low or high FF. Treatments included a ground crumble (988 µm) or crumble (1785 µm) during the starter phase (0-14d); while in the grower and finisher growth phases (14-28 and 28-46 d, respectively) either 50 or 80% IP (with the remaining 50 and 20% comprised of ground pellets or "fines", respectively) were provided. An outline depicting treatment structure can be found in Table 2.2. All diets were formulated to meet or exceed broiler recommendations and reflect nutritionally commercial relevancy [22]. Additionally, all diets were devoid of antibiotics and anticoccidials (Table 2.3).

Feed Manufacture

All feed was manufactured at the West Virginia University pilot feed mill. Treatments were batched and mixed (10 minute dry-mix and 10-minute wet mix) using a 0.907 tonne vertical single screw mixer [23]. Diets were steam conditioned using a 1.3 x 0.31 m short-term (10s) California Pellet Mill conditioner at 85° C and extruded through a 4.76 x 38 mm pellet die driven by a 40-horsepower California Pellet Mill [24]. These conditions created the high FF of 80% IP. For the starter growth phase, a portion of the 80% IP were ground through a single stage crumbler to create the high FF (crumbles). To create the low FF (ground crumbles), the gap width of the single stage crumbler was reduced further. For the grower and finisher growth phases, a portion of the 80% IP were passed through a single stage crumbler to create "fines" for creation of the low FF treatments (i.e. 50% IP).

Production rate was determined by measuring pellet volume post extrusion for 60 second sampling periods. Pellet Durability Index (PDI) and Modified Pellet Durability Index (MPDI) were performed using a Pfost tumbler box [25]. A New Holmen Pellet Tester (NHPT) was also utilized to determine percent survivability of pellets [26]. Each assay was performed in duplicate, 24 hours post pelleting. Particle size and particle size standard deviation were determined using a 100 g sample passed through a RO-TAP RX-29 for a 10 minute processing period [27, 28]. Descriptive data of these results are located in Table 2.4.

Feed was transported to the Mississippi State University poultry research unit for the 46 d grow-out. Upon receiving the grower and finisher diets, percent pellets were verified using a 22.68 kg representative sample passed through an American Society of

Agricultural Engineers #5 sieve. Prior to feeding, a portion of 80% IP and "fines" were hand-mixed to create low FF (50% IP) treatments for the grower and finisher growth phases. Hand-mixing was employed to prevent further attrition that would potentially occur if a mixer was implemented.

Live Performance

A total of 2,112 Ross x Ross 708 male broilers were obtained from a commercial hatchery [29] and randomly allocated to one of 176 pens (0.91 x 1.22m), creating a stocking density of 0.09 m^2/ bird. Feeder space access was modified using aluminum flashing to create 0.02 m/bird of access, in an effort to mimic commercial production using the methodologies described by Lemons and Moritz [10]. Mortality was collected twice daily; broilers and tube feeders were individually weighed at the end of each growth phase (14, 28, and 46 d, respectively). Performance variables measured were: feed intake/bird (FI), body weight gain/bird (BWG), ending BW, mortality corrected FCR, percent mortality, and CV of ending BW. All birds were reared using the environmental recommendations obtained from Ross 708 guidelines [30]. All methodologies were compliant with the Mississippi State University Institutional Animal Care and Use Committee (IACUC #15-099).

Statistical Analysis

All variables were analyzed within a randomized complete block design whereas blocks (n=11) were arranged by the location of pens within the house [31]. Due to the nature of the experimental design encompassing the main effects of FF presented in each growth phase that continuously built upon one another, multiple replications per

treatment were required in each block. The starter phase (0-14 d) was analyzed using one-way ANOVA for comparison of ground crumbles versus crumbles with 8 replications of each treatment occurring in each block (n= 88/treatment). Grower phase (14-28 d) means were analyzed using a 2 x 2 factorial arrangement with the main effects of the low or high FF presented in the starter (ground or crumble) and grower (50% or 80% IP) growth phases with 4 replications of each treatment occurring in each block (n= 44/treatment). Finisher phase (28-46 d) and overall (0-46 d) treatment means were analyzed as a 2 x 2 x 2 factorial arrangement with the main effects of low or high FF presented in the starter (ground or crumble), grower (50% or 80% IP), and Finisher (50% or 80% IP) growth phases with 2 replications of each treatment occurring per block (n=22/treatment). Significant main effect means ($P< 0.05$) were further separated using Fisher's protected LSD multiple comparison test.

Results and Discussion

Starter Performance (0-14 d)

The effects of FF on broiler performance in the starter (0-14 d) growth phase are presented in Table 2.5. Starting pen weight was not significantly different ($P=0.324$), allowing for all performance differences to be attributed to treatment FF. Broiler chicks fed crumbles (1785 µm) from 0-14 d resulted in an improved BW gain and ending BW ($P=0.034$) of 9 g. These chicks also had an increase in FI ($P=0.023$), but ultimately demonstrated a 0.02 reduction in 0-14 d FCR ($P=0.002$) as compared to chicks fed ground crumbles. Previous research has demonstrated improvements in broiler performance in the starting growth phase as a result of providing a higher quality FF [10, 19, 20]. However, in this previous work, comparisons are often made between birds fed

improved FF (e.g. crumbles or micropellets) and an unconditioned mash diet. Due to differences in manufacturing techniques (i.e. conditioning temperature, method of grinding, unconditioned mash, etc.), comparisons within and between studies can be difficult and are often confounded due to differences in nutrient availability [8, 9, 14-18]. Furthermore, previous research often fails to provide descriptive data regarding average particle size and standard deviations, also complicating comparisons within and between studies.

The current study demonstrated a 9 g improvement in 0-14 d BWG and 14 d ending BW (P=0.034, P=0.033, respectively; Table 2.5) when broilers were presented a crumble (1785 µm), as compared to broilers fed ground crumbles (988 µm). Lemons and Moritz (2016) demonstrated a numerical improvement of 4 g for 1-10 d BWG and 10d BW when broilers were provided a 1,191 µm (±1.85) crumble in comparison to a 951 µm (±1.91) crumble [10]. Conversely, Glover et al. (2016) demonstrated a 5 g improvement in BWG when broilers were provided 51% crumbles (≥ 1400 µm) in comparison to 71% crumbles (≥ 1400 µm) from 1-10 d [32]. Cerrate and cohorts (2009) provided broilers unconditioned mash, a crumbled diet (using 4.76mm diameter die), and micro pellets of 1.59 or 3.17 mm diameter from 0-13 d. Their work was important for comparison, as crumbled diets implemented a similar pellet die diameter as that utilized in the current study, as well as that in the research conducted by Lemons and Moritz [10] and Glover and cohorts [32]. Improvements in 0-13 d BW were observed when broilers were provided improved FF (i.e. crumbled diet or micropellets) compared to the unconditioned mash [20]. However, there was lack of performance separation between improved FF treatments of micropellets (regardless of diameter) and crumbled diets.

While Glover and cohorts and Cerrate and coauthors demonstrated differences in BW due to starter FF, these studies did not establish the average particle size (or standard deviations) associated with FF treatments [20, 32]. Specifically, Glover and cohorts (2016) provided the percentage of crumbles remaining on a 1400 µm sieve, whereas Cerrate and cohorts (2009) demonstrated the percentage of fines (using a 2000 µm sieve) for each treatment. While both studies provided a general description of FF, comparisons of performance results to that obtained in the current study (and similar projects) are difficult, as differences in performance may have been attributed to the crumble particle size. However, the distribution of crumbles and preferences in bird beak capacity may have confounded their results.

The current study demonstrated an increase in 0-14 d FI for broilers receiving 1785 µm crumbles (P=0.023, Table 2.5). Previous work has been conflicting, where some have established increased FI with improved FF [20] and other research has demonstrated the opposite [32]. While 0-14 d FI was increased in the current study, there was also a 0.02 reduction in FCR (P=0.002, Table 2.5), in favor of broilers receiving crumbles (1785 µm). This in agreement with previous literature which demonstrated a 0.02 [32] and 0.06 [10] reduction in FCR associated with improved FF. However, it is important to note that work conducted by Glover and cohorts (2016), exhibited decreased BW and FI when broilers were provided the improved FF (71 % crumbles; ≥1400µm), as previously outlined [32].

These data suggest feeding a crumble of 1785 µm for improved 0-14 d BWG and FCR, as well as 14 d ending BW. However, potential remains, as this may not be the optimal particle size for maximizing 0-14 d broiler performance; warranting continued

research. Furthermore, differences in strains may influence the optimal crumble particle size, based on bird beak capacity. In the aforementioned studies used for comparison, genetic strains of Hubbard x Cobb 500 [10, 32] and Cobb 500 [20] were utilized, which could have influenced their results. This could also complicate comparisons made between the previous studies utilizing Cobb 500 broilers and the current study, which utilized Ross x Ross 708.

Grower Performance (14-28; 0-28 d)

The effects of FF on broiler performance in the grower (14-28 d), as well as the starter and grower (0-28 d) growth phases are presented in Table 2.6. There were no starter x grower phase FF interactions demonstrated for 14-28 d or 0-28 d for any measured variable ($P>0.05$). Additionally, FF did not affect FCR in either growth phase ($P>0.05$). However, the main effect of FF presented in the grower phase demonstrated an improved 14-28 d ($P=0.001$, Table 2.6) and 0-28 d ($P=0.003$, Table 2.6) BW gain of 25 and 26 g, respectively, for broilers receiving 80% IP. These birds also resulted in a 26 g improvement in 28 d ending BW ($P=0.003$, Table 2.6), which may be attributed to the increased FI ($P=0.001$, Table 2.6) associated with these broilers exhibited by broilers receiving 80% IP. Similar to the current study, Dozier and cohorts (2010) demonstrated improvements in 15-28 d BW in Ross 708 male broilers as a result of providing broilers "high quality" pellets (88.92% PDI) in comparison to feeding mash, while birds fed "low quality" pellets (66.04% PDI) performed intermediate [7]. Attia and others (2014) also demonstrated improvements in 21-29 d BWG as a result of providing birds pelleted diets in comparison to an unconditioned mash [33]. While these studies demonstrated improvements in BW as a result of providing improved FF during the grower phases,

they also employed varied feed manufacturing techniques, which could have influenced the results. Specifically, Dozier and cohorts (2010) utilized different conditioning temperatures and sites of fat addition to create the FF qualities [7]. These techniques utilized to create changes in FF may have also resulted in conformational changes in nutrients, as a result, potentially affecting their bioavailability, and consequently FF effects on broiler performance [8, 9, 14-18].

While differences in BW and BWG were established in the current study due to grower FF, no improvements in 14-28 d or 0-28 d FCR were found ($P>0.05$; Table 2.6). Although this lack of FCR benefit during the grower growth phase is supported by previous literature [7], more recent literature has demonstrated improvements in grower FCR as a result of feeding improved FF [10, 33]. However, it is important to note that Lemons and Moritz (2016) fed crumbled diets (1096 or 2133 µm from 11-22 d) during this growth phase, not pellets as used in the current study [10]. Additionally, Attia and others (2014) demonstrated a tremendous decrease of approximately 0.30 for 21-29 d FCR; however, these results were obtained by feeding broilers unconditioned mash or pellets [33]. Due to increased temperatures associated with pelleting, soybean meal digestibility may have been improved by decreasing trypsin inhibitor complexes, thus explaining the drastic reduction in FCR [34].

Similar to the current study, Lilly and cohorts (2011) demonstrated that improvements in FF resulted in improvements in 21-38 d BW; they attributed this to increased FI due to FCR improvements being "minor" [9]. It is important to note that Lilly and cohorts (2011), as well as Lemons and Moritz (2016), utilized similar manufacturing techniques to maintain a constant plane of nutrition, such as that in the

current study [9, 10]. As previously stated, changes in manufacturing techniques employed with Dozier and cohorts (2010) and Attia and others (2014), may have resulted in nutrient conformational changes the would complicate comparisons to the current study. Regardless, benefits for BW due to FF seem to be more apparent for the grower phase in comparison to FCR. Understanding this relationship of FF on BWG, FI, and FCR during this grower phase is not fully understood, thus warranting further research.

Finisher and Overall Performance (28-46 & 0-46 d)

In Table 2.7, interaction means for three-way interactions during the finisher phase (d 28-46) will not be presented due to no significance established for any performance metric ($P>0.05$). However, probability values associated with the three-way interactions are listed at the bottom of Table 2.7, for reference. Probability values and means associated with the two-way interactions, as well as the marginal means of FF presented for each growth phase can be found in Table 2.7. Additionally, no significance was established for the three-way interactions for any performance metric during the entirety of the trial (d 0-46; $P>0.05$, Table 2.8). Therefore, three-way interaction means will not be presented; however, probabilities associated with these interactions can be found at the bottom of Table 2.8. Means and probability values associated with the two-way interactions, as well as marginal means of FF presented in each growth phase, are displayed in Table 2.8.

During the finisher phase (d 28-46), starter FF interacted with FF presented in the finisher growth phase for 46 d ending BW ($P=0.036$, Table 2.7). Specifically, feeding broilers ground crumbles (988 µm) from 0-14 d and 80% IP from 28-46 d optimized 46 d ending BW. However, feeding birds ground crumbles (988 µm) and 50% IP from 28-46d,

as well as crumbles (1785 µm) from 0-14 d and 80% IP from 28-46 d reduced 46 d ending BW. Birds fed crumbles (1785 µm) and 50% IP demonstrated intermediate 46 d BW. While not significant, FF presented in the grower and finisher growth phases tended to affect 46 d ending BW (P=0.055, Table 2.7). Broilers receiving 80% IP in the grower and finisher growth phases demonstrated the highest 46 d ending BW, followed by broilers receiving 50% IP in the grower and the finisher phases. However, when FF presented was altered, (i.e. 50% IP-Grower and 80% IP- Finisher or 80% IP-Grower and 50% IP-Finisher), 46 d ending BW was negatively impacted, with birds fed 80% IP during the grower and 50% IP in the finisher growth phase having the lowest 46 d ending BW.

For the main effects during the finisher growth phase, starter FF influenced finisher FCR, whereas chicks fed ground crumbles from 0-14 d resulted in a 0.02 decrease in 28-46 d FCR (P=0.029, Table 2.7). Additionally, starter FF tended to affect 28-46 d BWG (P=0.068, Table 2.7). Chicks receiving ground crumbles (988 µm) from 0-14 d demonstrated a higher 28-46 d BWG by 41 g, as compared to those fed crumbles (1785 µm). Lastly, finisher FF affected 46 d CV of BW (P=0.020), where broilers fed 50% IP from 28-46 d resulted in improved uniformity as compared to those receiving 80% IP.

Similarly to the interaction for d 46 ending BW observed during the finisher phase, starter FF (0-14 d) and finisher FF (28-46 d) tended to interactively affect 0-46 d BWG (P=0.068;Table 2.8). Broilers receiving ground crumbles from 0-14 d and 80% IP from 28-46 d resulted in the highest 0-46 d BWG. However, feeding broilers high FF (crumbles and 80% IP) or low FF (ground crumbles and 50% IP) resulted in the lowest

BW. Broilers fed crumbles (1785 µm) and 50% IP resulted in a 15 g improvement compared to these two treatment regimens (High and Low FF). Overall, at least a 73 g improvement was established for feeding ground crumbles (0-14 d) and 80% IP (28-46 d) was observed for 0-46 d BWG.

Examining the main effects on overall performance (d 0-46), broilers receiving 80% IP from 28-46 d resulted in a higher 0-46 d FI (P=0.009), as compared to broilers presented 50% IP. Overall (0-46 d) mortality was affected by FF presented in the grower (14-28 d) growth phase (P=0.012, Table 2.8). Broilers fed 80% IP had higher mortality (4.45% increase) than those fed 50% IP from 14-28 d (P=0.012, Table 2.8). Additionally, a trend for overall (0-46 d) mortality demonstrated that broilers receiving 80% IP from 28-46 d resulted in a higher incidence of mortality (3.13% increase) as compared to birds fed 50% IP during the finisher growth phase (P=0.074).

Perhaps the most interesting finding from the current study was the interaction between FF presented in starter and finisher growth phases to influence overall 46 d ending BW (P=0.036, Table 2.7, Figure 2.1). Additionally, there was a trend (P=0.068) for FF presented in the starter and finisher growth phase to affect 0-46 d BWG (Table 2.8). These interactions both demonstrated that broilers were able to overcome the performance deficit from receiving ground crumbles (988 µm) in the starter phase (0-14 d) when fed 80% IP in the finisher phase (28-46 d), resulting in the highest numerical 46d BW. While starter performance (0-14d) was decreased due to providing ground crumbles (988 µm), compensatory growth may have occurred when providing high quality FF in the finisher growth phase. However, broilers receiving crumbles (1785 µm) during the starter phase and 50% IP during the finisher growth phase resulted in a similar 46 d BW,

making the hypothesis of compensatory growth questionable. Improvements in quantitative genetics may have resulted in the necessity to decrease the rate of growth during the grow-out cycle, with similar results in BW, regardless of when this decrease occurs. While the results of the current study were unanticipated, research conducted by Choi and others (1986) supports this finding [21]. Their data demonstrated that broilers receiving mash in the starter period and pellets in the finishing period resulted in the highest BW. However, it is important to note that these improvements were seen using a Maniker strain, not the Ross x Ross 708 utilized in the current study. These data indicate that it may not be evolution of a genetic strain and that relationship between FF and broiler performance is complex.

A grower x finisher interaction for 46 d ending BW (P=0.055, Table 2.7, Figure 2.2) demonstrated that broilers provided 80% IP in the grower and finisher growth phases had the highest ending BW. However, broilers receiving 50% IP during these growth phases demonstrated a similar 46 d ending BW, with a decrease of only 8 g. Abdollahi and Ravindran (2013) documented decreased broiler performance when first adapting from 3 to 5 or 7 mm pellets [35]. These data suggest that consistency of FF may be as important (or more) than improved FF. Previous research has attributed BW improvements to providing higher quality FF during the finisher growth phase [7, 9-11]. However, these studies commonly utilized a pre-test diet [9, 11] or provided differing FF (i.e. “low” or “high”) in earlier growth phases (e.g. starter and grower) [10]. Based upon the findings of the current study, the potential of FF to interact may have significantly impacted these data. More importantly, these findings suggest how important it is that FF

research indicates the manufacturing techniques and the FF provided throughout the entire growout.

The main effect of starter FF was significant for FCR (P=0.029; Table 2.7), whereas broilers receiving ground crumbles (988 µm) demonstrated improved 28-46 d feed efficiency. However, overall (0-46 d) FCR was not affected by FF presented in each growth phase. Due to crumbles (1785 µm) improving 0-14 d FCR (Table 2.5), speculated compensatory growth resulting in improvements in BW may have occurred for broilers receiving ground crumbles in the starter growth phase, allowing for improvements in 28-46 d FCR when presented higher quality FF in the finisher growth phase (Table 2.7). Previous work has reported improved 0-13 d FCR as a result of feeding improved FF [20]. However, as with the current experiment, these benefits were diminished for overall growth (0-34 d and 0-41 d FCR); the authors speculated this to be attributed to compensatory growth.

Mortality was high throughout the study, perhaps due to the absence of antibiotics and anticoccidials in the diets [36]. However, significance was only demonstrated for overall performance (0-46 d) as a result of FF presented during the grower growth phase (P=0.012, Table 2.8). While each mortality case was not individually documented, necropsies confirmed the presence of necrotic enteritis during a spike in mortality during the grower growth phase. It is likely that the necrotic enteritis was a result associated with the use of used litter and/or the live coccidiosis vaccination administered at the commercial hatchery, causing a secondary infection due to coccidiosis [37].

The CV of ending BW during the finisher (28-46 d) growth phase demonstrated that broilers receiving the low FF resulted in a lowest CV (higher uniformity; P=0.020,

Table 2.7). This is in agreement with previous research [10, 32]. Authors of this previous work attributed this to competition present at the feed pan, as a result of restricting feeder space access, causing increase FI of IP for more dominant birds. Thus, leaving the remaining population to consume a higher percentage of fines, resulting in decreased growth and uniformity for broilers receiving high FF. While the exact economic impact is unknown, this could result in complications of automated broiler processing equipment [10]. Thus, an integrator may need to consider if improvements in BWG and ending BW associated with high quality FF outweigh the potential complications associated with the processing of less uniform broilers.

Summary

In conclusion, the current study demonstrated that feeding high quality FF in the starter and grower phases maximized performance during these respective phases. However, performance benefits were not as pronounced during the finisher phases, as demonstrated in previous research (Table 2.1). The most important result of this study was that FF presented in the starter (0-14 d) and finisher (28-46 d) growth phases has potential to interact and influence overall performance (0-46 d). Therefore, future research is warranted to further understand the relationship between FF presented in each growth phase; especially between the starter and finisher growth phase. However, the current experiment only implemented two FF presented in three growth phases utilizing one genetic strain. With this in mind, future research should implement intermediate variables to assist with providing a recommendation(s) to commercial integrators. Determining the optimal crumble particle size provided for the starter (0-14 d) growth phase to improve overall (d 46 +) performance could have dramatic impact on the

commercial industry and should be investigated. Additionally, the potential of feeding different IP percentages than those implemented in the current study (e.g. 50 and 80%) should be further investigated.

Conclusions and Applications

1. Feeding crumbles (1785 µm) during the starter (0-14 d) growth phase resulted in a 0.02 reduction in FCR as compared to feeding ground crumbles (988 µm). Feeding crumbles (1785 µm) during the starter (0-14 d) and 80% IP in the grower (14-28 d) growth phases resulted in a 9 g and 25 g BW improvement for these growth phases, respectively.

2. Starter (0-14 d) and finisher (28-46 d) FF interacted to affect 46 d ending BW. These data suggest feeding ground crumbles (988 µm) in the starter growth phase and 80% IP during the finisher to maximize 46 d ending BW. However, similar performance was achieved by providing crumbles (1785 µm) and 50% IP providing a viable solution for integrators if high FF (i.e. 80% IP) cannot be achieved. These treatments resulted in an approximate 56 g improvement in 46 d ending BW in comparison to other treatment combinations (e.g. ground crumbles and 50% IP or crumbles and 80% IP).

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Table 2.1 Summary of research using nutritionally common diets with modest improvements in FF.

Authors	Genetic Strain	FF Treatments	PDI[1]	Days Fed	Body Weight Improvements (per bird)	FCR Improvements
Lemons and Moritz (2016)	Hubbard x Cobb	40% IP[2] vs. 70% IP	74.23	23-38	102 grams	0.02
Glover et. al (2016)	Hubbard x Cobb	50% IP vs. 70% IP	86.6	22-38	NS[4]	0.06
Sellers et. al (2017)	Cobb 500 and Ross 708	50% IP vs. 80% IP	NR[3]	28-42	80 grams	0.08

[1]PDI=Pellet Durability Index (ASAE 1997a).
[2]IP=Intact Pellets.
[3]NR=Not Reported.
[4]NS=No Significance.

Table 2.2 Treatment outline of FF presented in each growth phase[1].

Treatment	Growth Phase		
	Starter (0-14 d)	Grower (14-28 d)	Finisher (28-46 d)
1	Ground Crumbles[2] (988 µm)	50% IP[4,5]	50 % IP
2			80 % IP
3		80% IP[5]	50 % IP
4			80 % IP
5	Crumbles[3] (1785 µm)	50% IP	50 % IP
6			80 % IP
7		80% IP	50 % IP
8			80 % IP

[1]Descriptive feed manufacture data located in Table 4.
[2]Ground Crumbles= 988µm; Performed in duplicate using ASAE 1997b.
[3]Crumbles=1785 µm; Performed in duplicate using ASAE 1997b.
[4]IP=Intact Pellet.
[5]Determined utilizing American Society of Agricultural Engineers #5 sieve.

Table 2.3 Diet composition of starter, grower, and finisher diets fed to male Ross x Ross 708 male broilers.

	Starter (0-14 d)	Grower (14-28 d)	Finisher (28-46 d)
Ingredient	Inclusion, (%)	Inclusion, (%)	Inclusion, (%)
Corn	49.91	55.28	58.41
Soybean Meal (48% CP)	39.76	32.63	28.96
Corn Dried Distillers Grains & Solubles	3.00	4.00	4.00
Meat & Bone Meal (50% CP)	2.00	3.00	3.00
Animal & Vegetable Blend Fat	1.94	2.34	3.33
Dicalcium Phosphate	1.38	0.90	0.67
Limestone	0.59	0.42	0.34
DL-Methionine	0.34	0.31	0.24
Sodium Chloride	0.31	0.28	0.29
Vitamin & Trace Mineral Premix[1]	0.27	0.27	0.27
Sodium Bicarbonate	0.24	0.25	0.23
L-Lysine HCl	0.14	0.17	0.12
L-Threonine	0.07	0.08	0.05
Selenium Premix	0.02	0.02	0.02
Phytase	0.02	0.02	0.02
Choline Chloride	0.01	0.03	0.05
Calculated Nutrients			
Metabolizable Energy (kcal/kg)	3,000	3,100	3,200
Crude Protein (%)	24.32	22.10	20.48
Digestible Lysine (%)	1.28	1.15	1.02
Digestible TSAA (%)	0.97	0.89	0.79
Digestible Threonine (%)	0.83	0.76	0.68
Calcium (%)	0.81	0.72	0.63
Available Phosphorus (%)	0.41	0.36	0.32
Sodium (%)	0.22	0.22	0.22
Analyzed Nutrients			
Crude Protein[2] (%)	25.53	22.48	22.34
Crude Fat[3](%)	4.19	4.94	6.21
Total Calcium[3] (%))	0.70	0.72	0.59
Non-phytate phosphorus[4] (%)	0.41	0.34	0.32
Phytase Activity[3] (FTU/kg)	1,830	2,570	2,070

[1] Supplied per kg of diet: manganese, 0.02%; zinc 0.02%; iron, 0.01%; copper, 0.0025%; iodine, 0.0003%; selenium, 0.00003%; folic acid, 0.69mg; choline, 386mg' riboflavin, 6.61mg; biotin, 0.03mg; vitamin B6, 1.38mg; niacin, 27.56mg; pantothenic acid, 6.61mg; thiamine, 2.20mg; manadione, 0.83mg; vitamin B12, 0.01mg; vitamin E, 16.53 IU; vitamin D3, 2133 ICU; vitamin A, 7716 IU.
[2]Values are means of duplicate samples obtained at Mississippi State University using a LECO FP-528.
[3]Values are means of duplicate samples obtained from New Jersey Feed Labs (Ewing Township, NJ).
[4]Non-phytate phosphorus determined used the following equation: nPP= [Total Phosphorus – (.282 x Phytate)] x 100.

Table 2.4 Descriptive feed manufacture data for all diets fed in each growth phase throughout the experiment.

Phase	Conditioning Temperature (°C)	Production Rate (tonne/hr)	Average NHPT[1] (%)	Average PDI[2] (%)	Average MPDI[3] (%)	Feed Form	Average Particle Size[4] (µm) ± SD
Starter	85	0.982	86.40	87.78	84.43	Ground Crumbles	988 ± 1.94
						Crumbles	1785 ± 2.06
Grower	85	0.898	89.60	90.72	88.19	Fines[5]	962 ± 1.98
						Pellets	4589 ± 1.19
Finisher	85	0.819	71.73	81.46	76.02	Fines	937 ± 1.99
						Pellets	4510 ± 1.23

[1] New Holman Pellet Tester; performed for 30 s processing period using ASAE 1997a; performed in duplicate.
[2] Pellet Durability Index (Pfost tumbler); performed for 10 m processing period using ASAE 1997a; performed in duplicate
[3] Modified Pellet Durability Index (Pfost tumbler); performed for 10 m processing period using ASAE 1997a; performed in duplicate.
[4]Pellets were ground using single stage roller mill; Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[5]Intact pellets were ground using a roller mill for creation of fines during grower and finisher growth phases to create 50% intact pellets treatment.

Table 2.5 Comparisons of birds fed crumbles or ground crumbles on starter (0-14 d) broiler chick performance.

Treatment[1]	Starting Pen Weight[2] (kg)	Feed Intake/bird (kg)	BWG[3]/bird (kg)	14 d Ending BW[4] (kg)	FCR[5] (kg/kg)	Percent Mortality (%)	d 14 CV[6] of Ending BW (%)
Ground Crumbles[7]	0.480	0.490[b]	0.377[b]	0.417[b]	1.290[a]	3.927	10.057
Crumbles[8]	0.481	0.499[a]	0.386[a]	0.426[a]	1.272[b]	3.902	10.327
SEM[9]	0.0003	0.002	0.003	0.003	0.003	0.343	0.342
ANOVA P-Value	0.324	0.023	0.034	0.033	0.002	0.960	0.589

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$).
[1]All diets were pelleted @ 85°C and ground using a roller mill.
[2]Starting Pen weight consisted of 12 Ross x Ross 708 male broilers/pen.
[3]BWG=Body Weight Gain.
[4]BW=Body Weight.
[5]FCR= Feed Conversion Ratio, corrected for mortality.
[6]CV= Coefficient of Variation for ending BW.
[7]Ground Crumbles= 988 µm; created by grinding of intact pellets using a single stage roller mill. Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[8]Crumbles= 1785 µm; created by grinding of intact pellets using a single stage roller mill. Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[9]SEM=Standard Error of the Mean.

Table 2.6 Comparisons of birds fed crumbles or ground crumbles (0-14 d) and 50% IP[1] or 80% IP (14-28 d) on grower (14-28; 0-28 d) broiler performance.

Starter FF[2,3]	Grower FF[4]	14-28 d Feed Intake/bird (kg)	0-28 d Feed Intake/bird (kg)	14-28 d BWG[5]/bird (kg)	0-28 d BWG/bird (kg)	28 d Ending BW[6] (kg)	14-28 d FCR[7]	0-28 d FCR	14-28 d Percent Mortality (%)	0-28 d Percent Mortality (%)	d 28 CV[8] of Ending BW (%)
Marginal Means-Starter Feed (0-14 d) Main Effect											
Ground Crumbles[9]		1.651	2.143	1.104	1.480	1.520	1.482	1.430	3.330	7.071	8.45
Crumbles[10]		1.647	2.162	1.100	1.487	1.527	1.488	1.428	4.183	8.902	9.01
[8]Marginal Means-Grower Feed (14-28 d) Main Effect											
50% IP[11]		1.627[b]	2.131[b]	1.089[b]	1.470[b]	1.510[b]	1.488	1.430	3.572	6.944	8.746
80% IP		1.671[a]	2.174[a]	1.114[a]	1.496[a]	1.536[a]	1.482	1.428	3.942	9.028	8.710
SEM[12]		0.008	0.008	0.005	0.006	0.006	0.003	0.002	0.489	0.984	0.261
Starter (0-14 d) x Grower (14-28 d) Interaction Means											
Ground Crumbles	50% IP	1.628	2.122	1.092	1.467	1.507	1.485	1.430	3.005	6.250	8.406
	80% IP	1.674	2.164	1.115	1.493	1.533	1.479	1.430	3.655	7.891	8.485
Crumbles	50% IP	1.626	2.141	1.086	1.473	1.513	1.492	1.430	4.139	7.639	9.086
	80% IP	1.668	2.184	1.113	1.500	1.540	1.484	1.426	4.228	10.164	8.936
SEM[9]		0.011	0.011	0.007	0.008	0.008	0.005	0.003	0.691	1.392	0.369
Main Effect and Interaction Probabilities											
Starter FF		0.744	0.088	0.523	0.418	0.415	0.229	0.513	0.227	0.198	0.136
Grower FF		0.001	0.001	0.001	0.003	0.003	0.147	0.536	0.597	0.145	0.925
Starter FF x Grower FF		0.850	0.952	0.738	0.990	0.996	0.891	0.634	0.688	0.753	0.759

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$).
[1]IP=Intact Pellets.
[2]FF=Feed Form.
[3]Starter diets were conditioned @ 85°C and ground using a single stage roller mill.
[4]Grower diets were conditioned @ 85°C.
[5]BWG=Body Weight Gain.
[6]BW=Body Weight.
[7]FCR= Feed Conversion Ratio, corrected for mortality.
[8]CV= Coefficient of Variation for ending BW.
[9]Ground Crumbles= 988 µm; created by grinding of intact pellets using a single stage roller mill. Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[10]Crumbles= 1785 µm created by grinding of intact pellets using a single stage roller mill. Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[11]Intact pellets were ground for creation of fines to create a treatment of 50:50 Pellets:Fines by hand mixing fines to 80% IP treatments prior to feeding.
[12]SEM=Standard Error of the Mean.

Table 2.7 Comparisons of birds fed crumbles or ground crumbles (0-14 d) and 50% IP[1] or 80% IP (14-28 and 28-46 d) on finisher (28-46 d) broiler performance.

Starter FF[2,3]	Grower FF[4]	Finisher FF[5]	Feed Intake/Bird (kg)	BWG[6]/bird (kg)	46 d Ending BW[7] (kg)	FCR[8]	Percent Mortality (%)	d 46 CV[9] of Ending BW (%)
Marginal Means- Starter (0-14 d), Grower (14-28 d), and Finisher (28-46 d) Main Effects								
Ground Crumbles[10]	-	-	3.308	1.849	3.353	1.796[b]	1.691	7.769
Crumbles[11]			3.284	1.808	3.328	1.818[a]	1.583	8.302
-	50% IP[12]	-	3.302	1.847	3.346	1.798	1.785	8.057
	80% IP		3.290	1.811	3.335	1.816	1.489	8.013
-	-	50% IP	3.274	1.821	3.331	1.799	1.312	7.602[b]
		80% IP	3.317	1.837	3.350	1.815	1.962	8.468[a]
SEM[13]			0.021	0.016	0.018	0.007	0.388	0.256
Starter (0-14 d) x Grower (14-28 d) Interaction Means								
Ground Crumbles	50% IP	-	3.318	1.870	3.365	1.779	1.929	7.792
	80% IP		3.297	1.828	3.341	1.812	1.453	7.745
Crumbles	50% IP		3.284	1.823	3.326	1.817	1.643	8.323
	80% IP		3.282	1.794	3.329	1.819	1.524	8.280
Starter (0-14 d) x Finisher (28-46 d) Interaction Means								
Ground Crumbles	-	50% IP	3.266	1.826	3.316[b]	1.793	1.209	7.120
		80% IP	3.350	1.872	3.390[a]	1.798	2.173	8.417
Crumbles	-	50% IP	3.284	1.815	3.347[ab]	1.805	1.415	8.084
		80% IP	3.284	1.802	3.309[b]	1.831	1.752	8.519
Grower (14-28 d) x Finisher (28-46 d) Interaction Means								
-	50% IP	50% IP	3.302	1.854	3.363	1.789	1.360	7.572
		80% IP	3.302	1.841	3.329	1.807	2.211	8.543
-	80% IP	50% IP	3.247	1.789	3.300	1.809	1.264	7.633
		80% IP	3.332	1.833	3.371	1.822	1.714	8.393
SEM			0.030	0.022	0.026	0.010	0.549	0.362
Main Effect and Interaction Probabilities								
Starter FF			0.281	0.068	0.328	0.029	0.846	0.145
Grower FF			0.612	0.115	0.720	0.084	0.591	0.902
Finisher FF			0.099	0.450	0.458	0.124	0.240	0.020
Starter FF x Grower FF			0.854	0.740	0.584	0.141	0.746	0.995
Starter FF x Finisher FF			0.275	0.192	0.036	0.314	0.569	0.237
Grower FF x Finisher FF			0.141	0.223	0.055	0.809	0.716	0.771
Starter FF x Grower FF x Finisher FF			0.147	0.106	0.272	0.831	0.447	0.626

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$).
[1]IP=Intact Pellets.
[2]FF=Feed Form.
[3]Starter diets were conditioned @ 85°C and ground using a single stage roller mill.
[4]Grower diets were conditioned @ 85°C.
[5]Finisher diets were conditioned @ 85°C.
[6]BWG=Body Weight Gain.
[7]BW=Body Weight.
[8]FCR= Feed Conversion Ratio, corrected for mortality.
[9]CV= Coefficient of Variation for ending BW.
[10]Ground Crumbles= 988 µm; created by grinding of intact pellets using a single stage roller mill. Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[11]Crumbles= 1785 µm created by grinding of intact pellets using a single stage roller mill. Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[12]Intact pellets were ground for creation of fines to create a treatment of 50:50 Pellets:Fines by hand mixing fines to 80% IP treatments prior to feeding.
[13]SEM=Standard Error of the Mean.

Table 2.8 Comparisons of birds fed crumbles or ground crumbles (0-14 d) and 50% IP[1] or 80% IP (14-28 and 28-46 d) on overall (0-46 d) broiler performance.

Starter FF[2,3]	Grower FF[4]	Finisher FF[5]	Feed Intake/Bird (kg)	BWG[6]/bird (kg)	FCR[7] (kg/kg)	Percent Mortality (%)
Marginal Means- Starter (0-14 d), Grower (14-28 d), and Finisher (28-46 d) Main Effects						
Ground Crumbles[8]	-	-	5.446	3.313	1.633	9.280
Crumbles[9]			5.423	3.276	1.637	11.837
-	50% IP[10]	-	5.438	3.299	1.638	8.333[b]
	80% IP		5.432	3.291	1.632	12.784[a]
-	-	50% IP	5.393[b]	3.277	1.631	8.996
		80% IP	5.447[a]	3.313	1.638	12.121
SEM[11]			0.025	0.019	0.004	1.218
Starter (0-14 d) x Grower (14-28 d) Interaction Means						
Ground Crumbles	50% IP	-	5.444	3.332	1.634	7.197
	80% IP		5.447	3.295	1.631	11.364
Crumbles	50% IP		5.431	3.266	1.642	9.470
	80% IP		5.415	3.287	1.632	14.205
Starter (0-14 d) x Finisher (28-46 d) Interaction Means						
Ground Crumbles	-	50% IP	5.385	3.269	1.630	8.333
		80% IP	5.507	3.357	1.635	10.227
Crumbles		50% IP	5.401	3.284	1.632	9.659
		80% IP	5.446	3.269	1.641	14.015
Grower (14-28 d) x Finisher (28-46 d) Interaction Means						
-	50% IP	50% IP	5.404	3.302	1.631	6.439
		80% IP	5.472	3.296	1.644	10.227
	80% IP	50% IP	5.381	3.251	1.631	11.553
		80% IP	5.483	3.330	1.632	14.015
SEM			0.036	0.028	0.005	1.722
Main Effect and Interaction probabilities						
Starter FF			0.507	0.185	0.422	0.142
Grower FF			0.831	0.774	0.260	0.012
Finisher FF			0.009	0.188	0.199	0.074
Starter FF x Grower FF			0.758	0.301	0.485	0.869
Starter FF x Finisher FF			0.499	0.068	0.703	0.477
Grower FF x Finisher FF			0.416	0.128	0.251	0.701
Starter FF x Grower FF x Finisher FF			0.161	0.443	0.636	0.115

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$).
[1]IP=Intact Pellets.
[2]FF=Feed Form.
[3]Starter diets were conditioned @ 85°C and ground using a single stage roller mill.
[4]Grower diets were conditioned @ 85°C.
[5]Finisher diets were conditioned @ 85°C.
[6]BWG=Body Weight Gain.
[7]FCR= Feed Conversion Ratio, corrected for mortality.
[8]Ground Crumbles= 988 µm; created by grinding of intact pellets using a single stage roller mill. Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[9]Crumbles= 1785 µm created by grinding of intact pellets using a single stage roller mill. Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[10]Intact pellets were ground for creation of fines to create a treatment of 50:50 Pellets:Fines by hand mixing fines to 80% IP treatments prior to feeding.
[11]SEM=Standard Error of the Mean

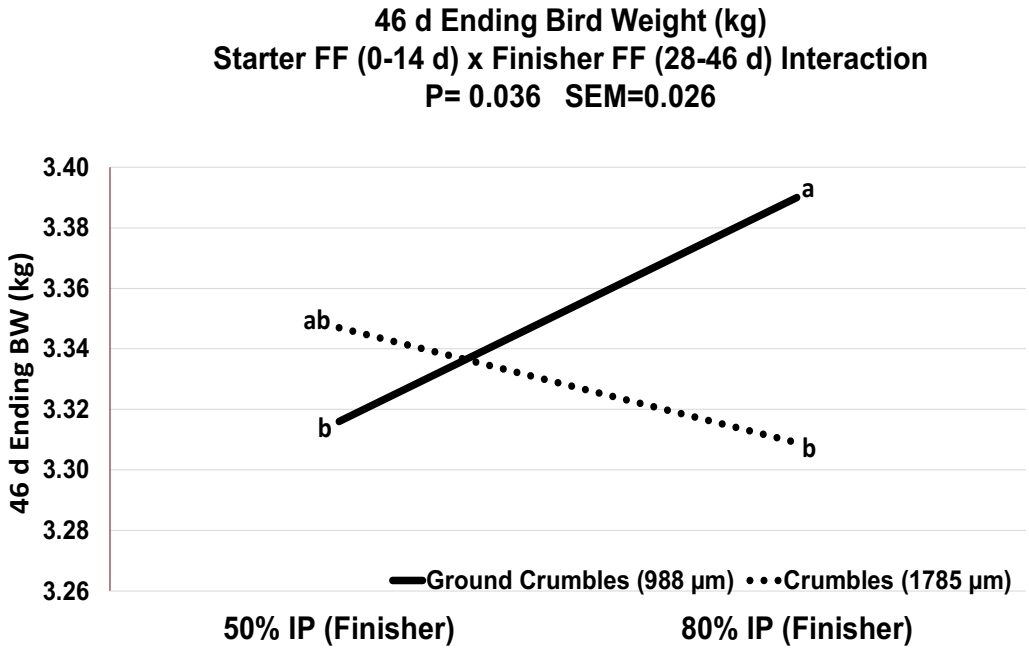

Figure 2.1 Interactive effects of birds fed crumbles or ground crumbles (0-14 d) and 50% IP [1,2] or 80% IP (28-46 d) on 46 d ending BW.

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$).
[1]IP=Intact Pellets.
[2]Intact pellets were ground for creation of fines to create a treatment of 50:50 Pellets:Fines by hand mixing fines to 80% IP treatments prior to feeding.

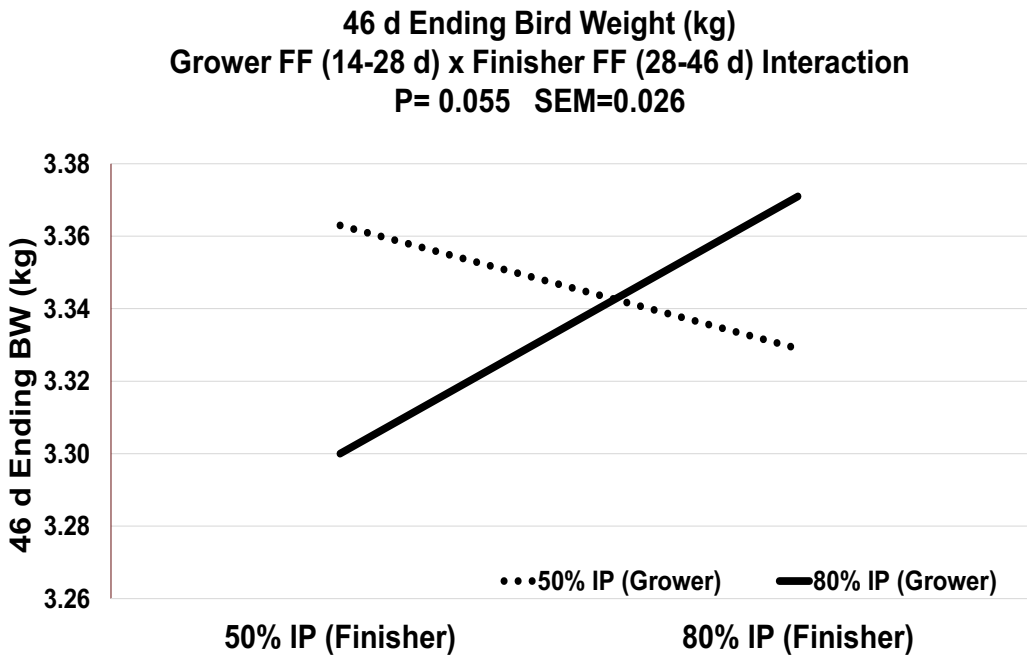

Figure 2.2 Interactive effects of birds fed 50% IP[1,2] or 80% IP (14-28 and 28-46 d) on 46 d ending BW.

[1]IP=Intact Pellets.
[2]Intact pellets were ground for creation of fines to create a treatment of 50:50 Pellets:Fines by hand mixing fines to 80% IP treatments prior to feeding.

CHAPTER III

EFFECTS OF CRUMBLE PARTICLE SIZE ON 0-14 D ROSS X ROSS 708 MALE BROILER PEFORMANCE

Summary

Recent research in our laboratory demonstrated that particle size of crumbles fed from 0-14 d influenced overall (0-46 d) performance. However, the optimal crumble particle size has not been identified in previous literature and represents an important void, as this is a critical stage in a broiler's lifecycle. Therefore, two experiments were conducted to evaluate the effects of crumble particle size on 0-14 d broiler performance in an effort to determine the optimal crumble particle size. Both experiments utilized Ross x Ross 708 male broiler chicks that were provided diets varying in crumble particle size from 1202 to 2172 µm (experiment 1) or 1174 to 3736 µm (experiment 2). Performance variables were analyzed with a randomized complete block design using one-way ANOVA. Improvements were most apparent for FCR with an associated 0.03 improvement in both experiments when broilers were provided crumbles of 1760 or 2172 µm (experiment 1) or crumbles larger than 2257 µm (experiment 2). Additionally, a 30 g improvement associated with ending BW and BW gain were demonstrated in experiment 2 for broilers receiving crumbles greater than 2800 µm. However, linear relationships for 0-14 d FCR, ending BW, and BW gain for experiments 1 and 2 demonstrate that the optimal particle size may not have been achieved during the current experiments.

Therefore, future research should focus on further expanding the range of particle size tested (beyond 3700 µm) from 0-14 d to identify the optimal crumble particle size during this growth phase.

Description of the Problem

While all facets of broiler production have become more efficacious, the improvements associated with quantitative genetics have tremendously improved today's broiler [1-4]. These improvements in broiler performance have lowered the production days required to meet "targeted demands" for respective markets while keeping production prices similar to that of the early 1950s [4,5]. However, improvements in genetic potential have resulted in changes in the nutritional requirements for broilers [6]. Therefore, it is also plausible that feed form (FF) should be adjusted to maximize broiler performance due to improvements in current genotypes.

Feeding pelleted diets is a common practice in today's broiler industry due to a magnitude of research demonstrating performance benefits associated with this improved FF [7-16]. However, FF presented in the early phases of a broiler's life is often less of a concern in the commercial industry with a smaller crumble particle size being typically implemented to ensure feed consumption. The starter phase (<14 d) represents a critical stage in a broiler's lifecycle. During the starter phase, the gastrointestinal tract, particularly the small intestine, is forming at a tremendous rate [17]. Due to the decreased time required for reaching targeted markets, gastrointestinal tract formation in the starter phase is critical for improved digestion to maximize performance [5, 18]. Additionally, digestive enzyme efficacy is limited during early stages of a broiler's life, creating a major concern surrounding the digestion and absorption of nutrients [19]. While it has

been generally accepted that broilers consume feed based on beak capacity [20, 21], research identifying the optimal particle size is void. Abdollahi and Ravindran outlined the potential to improve broiler performance in different growth phases by determining the optimal particle size for each respective phase [22]. Due to the vast improvements in commercial broilers genetics, the optimal particle size may be larger than originally conceived by commercial integrators.

Research pertaining to starter FF quality is limited in comparison to research pertaining to the finishing growth phases. Cerrate and cohorts demonstrated improvements in BW and FCR when providing improved FF (i.e. micropellets or crumbles) during the prestarter (0-7 d) and starter growth phases (0-13 d) [23, 24]. Additionally, Lemons and Moritz demonstrated improvements in d 0-10 FCR when broilers were provided a crumble of 1191 vs. 951 μm [14].

Recently, Lemons and coauthors demonstrated improvements in 0-14 d BW, BW gain, and FCR when feeding crumbles of 1785 vs. 988 μm [25]. One major finding from this work was the impact of starter FF to interact with FF presented in the finisher growth phase to influence 46 d BW. An interaction within this work demonstrated the importance for integrators to be cognizant of FF presented during the early stages of a broiler's life. While previous research has demonstrated improvements in early performance when broiler chicks were provided high FF, comparisons of results between studies is difficult due to differences in methodology for feed manufacture. Differences in genetic strains and failure to adequately describe average particle size and the resulting distribution (standard deviation) of crumbles further complicates this comparison. Additionally, the effect of crumble particle size on gastrointestinal tract morphology are

not well represented in the previous literature in comparison to the effects of ingredient particle size on gastrointestinal tract morphology. Therefore, two experiments were conducted to determine the effects of crumble particle size on 0-14 d Ross x Ross 708 male broiler gastrointestinal morphology and performance; with the primary objective being determination of the optimal crumble particle size.

Materials and Methods

For this research, two experiments were conducted that utilized common feed manufacture and bird husbandry techniques; which are described in the sections below. When appropriate, methods specific to a particular experiment are noted.

Feed Manufacture

Diet Preparation

Feed was manufactured at the West Virginia University pilot feed mill and transported to the Mississippi State University poultry research unit for the live performance experiments. One, nutritionally common diet (Table 3.1) was batched (n=2/experiment) and mixed (10 min dry mix; followed by a 10 min wet mix) using a one-ton vertical single screw mixer (mixer capacity= 907.2 kg) [26]. A common diet formulation (Table 3.1) that reflected commercial relevancy was utilized in both experiments and met or exceeded broiler recommendations [27].

Treatment Creation

Diets were steam conditioned using a 1.3 x 0.31 m short-term (10s) California Pellet Mill conditioner at 82 °C and extruded through a 4.76 x 44 mm pellet die driven by a 40-horsepower California Pellet Mill [28]. Pelleted diets were sacked off, weighed to

22.68 kg, then sequentially and evenly distributed to pallets designated for each crumble particle size. This was performed in an effort to create a homogeneous mixture prior to crumbling, to eliminate potential confounding effects. Production rate was determined by measuring pellet volume post extrusion for a 60 s sampling period. A New Holmen Pellet Tester was utilized to determine percent survivability of pellets [29]. This assay was performed in duplicate, 24 h post pelleting, for each batch of production (n=2/experiment). The average production rate and percent survivability of pellets is located in Table 3.2.

Particle sizes associated with each treatment were created using a single stage crumbler, with varying gap widths, for both experiments [30]. In experiment 1, rolls were adjusted to a gap width (almost touching) that would produce a small crumble for creation of treatment 1. Treatments 2 through 5 were created by incrementally increasing the gap width of rolls by ¼ turn, in chronological order. In experiment 2, the opposite approach was conducted. Rolls were adjusted to a large gap (~ 4 mm width) where pellets would be partially crumbled for the creation of the largest crumble particle size (treatment 8). The gap width between the rolls was then decreased by ¼ turn, in sequential order to create treatments 7 through 1. This approach was used in an effort to create a stepwise decrease in particle size. Average particle size and particle size standard deviation were determined using a Tyler RO-TAP RX-29 for a 10 minute processing period and performed in duplicate using ASAE method S319.2 [31, 32]. Average particle size and standard deviation of treatments for each experiment are also located in Table 3.2.

Due to the larger particle size treatments utilized in experiment 2, classification of percent pellets, crumbles, and fines was performed using the methodology described by Lemons and Moritz and Glover and cohorts [14, 15]. Descriptive data from sieve classification for experiment 2 are also located in Table 3.2.

Live Performance

All methodologies utilized in the current experiments were compliant with the Mississippi State University Institutional Animal Care and Use Committee (IACUC #15-099). Experiment 1 was conducted in the winter; whereas, experiment 2 was conducted in the early spring.

Experiment 1

A total of 1,600 Ross x Ross 708 male broilers were obtained from a commercial hatchery [33] and equally (randomly) allocated to 80 pens (0.91 x 1.22m; 16 pens/treatment). Broilers were reared using the environmental recommendations outlined by Aviagen [34] in pens containing used litter that had been top-dressed with pine shavings. Broilers were offered feed for *ad libitum* consumption on feed trays from 0-7 d and transitioned to tube feeders on d 7. Mortality was collected twice daily; broilers and tube feeders were individually weighed at d 14. Performance variables measured included: feed intake/bird (FI), body weight gain/bird (BWG), ending BW, mortality corrected FCR, percent mortality, and d 14 pen CV of ending BW.

Experiment 2

A total of 1,920 Ross x Ross 708 male broilers were obtained from a commercial hatchery [33] and equally (randomly) allocated to 96 pens (0.91 x 1.22m; 12

pens/treatment). Methodology utilized in experiment 1 was mirrored in experiment 2, with the only difference being the addition of a d 7 weigh day to calculate the following: FI (d 0-7, d 7 -14, and d 0-14), BWG (d 0-7, d 7 -14, and d 0-14), ending BW (d 7 and d 14) , mortality corrected FCR (d 0-7, d 7 -14, and d 0-14) , percent mortality (d 0-7, d 7 -14, and d 0-14) , and pen CV of ending BW (d 7 and d 14).

Gastrointestinal morphology

Experiment 1

After individual weighing occurred on d 14, pen means were determined. One bird per pen (± 10 g of the pen's mean BW) was selected and tagged for d 15 gastrointestinal morphology measurements (16 replications per treatment). Broilers were euthanized via CO_2 asphyxiation, individually weighed, and respective organs were excised. Variables measured included duodenum, jejunum, and ileum length as well as the weights of the gizzard, proventriculus, pancreas, duodenum, jejunum, and ileum for determination of relative organ weight (relative to broiler BW). The pH of the gizzard and ileum contents was determined utilizing a pH probe [35] prior to removal of the digesta for weighing of organs to occur.

Experiment 2

Similarly to experiment 1, on d 14 one bird per pen (± 10 g of the pen's mean BW) was selected and tagged for d 15 gastrointestinal morphology measurements (12 replications per treatment). All other methodology and variables were consistent with that described for experiment 1.

Statistical Analysis

Experiment 1 consisted of five treatments, whereas experiment 2 consisted of eight treatments; however, for both experiments, treatments varied only in crumble particle size (Table 3.2). Treatments were fed from 0-14 d in both experiments. For each experiment, all variables were analyzed with a randomized complete block design using one-way ANOVA [36]. Blocking criterion (n=16 for experiment 1; n=12 for experiment 2) consisted of location of pens within the house. Significant treatment means ($P < 0.05$) were further analyzed using Fisher's protected LSD multiple comparison test. Alpha was designated as 0.05, and letter superscripts were used to denote differences among treatment means. Additionally, linear, quadratic, and cubic regression analyses were performed for each live performance metric using treatment means (n=5 for experiment 1; n=8 for experiment 2).

Results and Discussion

Gastrointestinal Morphology

Experiment 1

Comparisons of crumble particle effects on d 15 gastrointestinal morphology and relative organ weight are presented in Table 3.3. While differences in d 15 organ weights were present (data not presented), when placed on an relative weight basis, only relative jejunum weight was deemed significant (P=0.039, Table 3.3). Broilers receiving crumbles of 1760 μm resulted in the highest relative jejunum weight in comparison to all other treatments (P=0.039, Table 3.3). Although the effects of ingredient particle size on gastrointestinal morphology are well established [37], research examining the effects of FF on gastrointestinal morphology is not present in recent literature making comparisons

with the current study difficult. Nir and cohorts demonstrated lower relative duodenum weights when broilers were presented a diet consisting of "coarse" particles [38]. While these aforementioned findings were present for the duodenum weight, it is an interesting comparison as the current study demonstrated an opposite effect with an increased relative jejunum weight as broilers were fed a larger crumble particle size (i.e. 1760 µm). However, this effect was not consistent for broilers receiving crumbles of the highest average particle size of 2172 µm; making an associated mechanism of action difficult to describe.

Broilers receiving an average crumble particle size of 1202 µm resulted in a significantly lower ileum pH than other treatments; with 1760 µm crumbles performing intermediate (P=0.004, Table 3.3). Looking at the effects of corn particle size, Nir and cohorts demonstrated a lower intestinal pH when mash diets were fed which is in agreement with the current study [39]. While previous research examining the effects of ingredient particle size have primarily focused on gizzard pH, which was not significant in the current experiment, perhaps the mechanism of action occurring for ileum pH can partially be explained. Research has demonstrated that feeding fine particles results in decreased retention time in the gizzard making it more of a transit organ rather than a grinding organ [40, 41]. Feeding coarse particles impacts gut motility increasing the retention rate in the gizzard allowing more digestive enzymes to act upon the substrate [41-43]. While one would believe this decreased time in the gizzard would result in a higher pH (less acidic), perhaps the decreased retention time in the gut would result in less opportunity for pancreatic buffers to neutralize the pH explaining the lower ileum pH associated with broilers receiving crumbles of 1202 µm.

Experiment 2

Comparisons of crumble particle effects on d 15 gastrointestinal morphology and relative organ weight are presented in Table 3.4. It is important to note that while not significant, a trend for relative jejunum weight was demonstrated similarly to experiment 1 (P=0.052, Table 3.4). Conversely, ileum pH was not significant as demonstrated in experiment 1.

It is important to note that both experiments employed measurements (e.g. small intestine lengths, pH, and relative organ weight) commonly implemented in previous literature examining the effects of ingredient particle size on gastrointestinal morphology [41, 44]. However, differences in gastrointestinal morphology due to crumble particle size were not as pronounced as these aforementioned studies. Additionally, while relative organ weight in experiment 1 were greater than observed in experiment 2, the authors speculate that this may be partially due to differences in d 15 BW between the experiments influencing resulting relative organ weights. Although the current study performed common morphology measurements to explain presumed differences in starter performance, no consistent changes in morphology were apparent for either experiment. Therefore, the current experiment suggests differences in starter performance due to crumble particle size are not primarily caused by morphological changes within the gastrointestinal tract.

Live Performance

Experiment 1

Results for 0-14 d broiler performance are located in Table 3.5. Starting pen weight (d 0) was not significant, allowing all performance benefits to be attributed to differences in average crumble particle size (P=0.809, Table 3.5). Improvements in BW, BW gain, FI,

percent mortality, and CV of ending BW were not established in the current experiment and will not be discussed (P>0.05, Table 3.5). However, broilers receiving an average crumble particle size of 1760 or 2172 µm demonstrated improved 0-14 d FCR of approximately 0.03 (P=0.0001, Table 3.5) in comparison to treatments receiving a smaller average crumble particle size (1202, 1135, or 1675 µm).

Cerrate and cohorts demonstrated improvements in FCR ranging from 9-15 pts when providing improved FF (i.e. micropellets or crumbles) to Cobb 500 male broilers during the prestarter (0-7 d) and starter growth phases (0-13 d) [23, 24]. Furthermore, Lemons and cohorts recently demonstrated a 0.03 FCR reduction utilizing Ross x Ross 708 male broilers when feeding crumble particle sizes of 1785 vs. 988 µm [25]. Contrary to the current experiment, these researchers found improvements in early (d ≤ 14) BW and BW gain when providing improved FF to broilers [23-25]. However, similar to the current experiment, previous research demonstrated a 0.06 improvement in 0-10 d FCR, when providing crumbles of 1191 vs. 951 µm to Hubbard x Cobb 500 broilers; although, no improvements in BW or BW gain were found [14]. While some commonalities in the literature exist, some noteworthy differences also exist. For example, the FF tested in the current experiment covered a broader range and interestingly enough, at times, less magnitude of benefit as compared to previous work [14, 25]. Also, resulting performance benefits established for feeding improved FF in this early stage of life were not consistent across strain. Perhaps these differences are attributed, in part, to differences in bird beak capacity, depending upon strain and particle size tested. Regardless, the current experiment supports the feeding of increased crumble particle size, specifically to maximize FCR from 0-14 d.

In order to determine/establish an optimal particle size for this experiment, regression analyses were conducted; their associated probabilities are located in Table 3.6. These data demonstrated neither linear, quadratic, nor cubic relationships for the following metrics: FI, BW/gain, ending BW, and percent mortality (Table 3.6). Linear relationships demonstrated improved 0-14 d FCR as birds were fed increased crumble particle size ($P=0.034$, $R^2=0.822$, Table 3.6). While not significantly different with the ANOVA analysis, d 14 CV of Ending BW demonstrated a quadratic relationship in which chick uniformity decreased as particle size increased until 1760 µm, with the beginning of a plateau from 1760 to 2172 µm (P=0.022, R2= 0.999, Table 3.6). While previous research has primarily focused on the finishing phase, previous literature is in agreement with the current experiment demonstrating decreased uniformity as FF improved [14, 15, 25].

The results from experiment 1 suggest that integrators should provide an average crumble particle size of 1760 or 2172 µm to improve 0-14 d FCR. However, based on the significant linear relationship for 0-14 d FCR, our main objective of determining the optimal crumble particle size for 0-14 d Ross x Ross 708 male broiler performance was not achieved. Therefore, experiment 2 was conducted, to utilize a broader range of average crumble particle sizes (including larger sizes), in an effort to determine this optimal crumble particle size. Additionally, a d 7 weight was added to determine if compensatory growth was occurring for birds fed crumbles of a larger average particle size.

Experiment 2

Results for 0-7 d, 7-14 d, and 0-14 d broiler performance are located in Table 3.7. Once again, starting pen weight (d 0) was not significant allowing all performance benefits to be attributed to differences in average crumble particle size (P=0.090, Table 3.7). Percent mortality and CV of ending BW were not significant for any date range and will not be discussed in further length (P>0.05, Table 3.7). Although not significant, it is important to note the trend for 7-14 d mortality (P=0.081, Table 3.7). The authors speculate this increase in mortality is likely associated to the absence of antibiotics and anticoccidials, not differences in average crumble particle size. While each mortality case was not documented, necropsies performed throughout the experiment confirmed the presence of necrotic enteritis from 7-14 d.

Similarly to experiment 1, improvements in FCR were apparent throughout the experiment. While a general trend of FCR being improved as crumble particle size increased, the magnitude of these improvements was dependent on the day range of crumble presentation. Feed conversion ratio was improved approximately 0.05 from 0-7 d for broilers fed crumbles 2049 µm or greater as compared to broilers fed crumbles of 1174 or 1423 µm; with birds fed crumbles of 1883 µm performing intermediate (P=0.004, Table 3.7). However, FCR from 7-14 d resulted in further separation of treatments based on average crumble particle size presented (P<0.0001, Table 3.7). Broilers receiving crumbles of 3456 or 3736 µm demonstrated a reduction of 0.02 to 0.05 in 7-14 d FCR to birds fed crumbles ranging from 1174 to 2257 µm, with birds fed 2800 µm performing similar to those fed crumbles of 3736 µm (P<0.0001, Table 3.7). Finally, broilers receiving 3456 or 3736 µm resulted in the lowest numerical FCR, with

approximately 0.03 of associated improvement in comparison to birds fed crumbles of a smaller average particle size (1174, 1423, 1883, or 2049 µm; P<0.0001, Table 3.7). Broilers receiving 2257 or 2800 µm had an intermediate 0-14 d FCR. While both experiments 1 and 2 demonstrated a general improvement in 0-14 d FCR as crumble particle size increased, experiment 2 suggests that crumble particle size presented from 7 -14 d may be more important in regards to 0-14 d FCR than crumble particle size from 0-7 d. Furthermore, experiment 2 confirms that a larger particle size than tested in experiment 1 (i.e. 2172 µm) is optimal for increased 0-14 d FCR. It is important to note that while FCR for all particle sizes tested in experiment 2 were improved in comparison to those in experiment 1, the same trend of FCR improving as particle sizes increased was demonstrated. While it is likely that a further magnitude of improvement demonstrated in experiment 2 was attributed to better environmental conditions (e.g. early spring), both experiments confirm that crumble particle size plays a vital role in improving starter 0-14 d FCR.

In contrast to experiment 1, improvements in BW gain and ending BW were demonstrated throughout this experiment (P<0.0001, Table 3.7). Broilers fed crumbles 1883 µm or larger resulted in an approximate 8 g improvement in 0-7 d BW gain as compared to chicks fed crumbles of 1174 or 1423 µm (P<0.0001, Table 3.7). However, broilers receiving 2800 µm crumbles resulted in a greater 0-7 d BW gain in comparison to broilers fed 1883 µm; broilers fed 2049, 2257, 3456, and 3736 µm treatments performing intermediate (P<0.0001, Table 3.7). While d 7 ending BW demonstrated a similar response as 0-7 d BW gain, it is important to note broilers receiving 1423 µm crumbles performed similar to those fed 1883 or 2257 µm crumbles. However, broilers

receiving 2800 µm crumbles resulted in the highest d 7 ending BW; this was an 11 g improvement to broilers fed 1174 µm (P<0.0001, Table 3.7).

Similar to 7-14 d FCR, further separation among crumble particle size treatments for 7-14 d BW gain was observed (P<0.0001, Table 3.7). Broilers receiving crumbles of larger average crumble particle size (2800, 3456, or 3736 µm) resulted in improved 7-14 d BW gain of approximately 30 g as compared to broilers fed 1174 or 1423 µm (P<0.0001, Table 3.7). Broilers fed crumbles of intermediate particle size (1883, 2049, or 2257 µm) performed similar to those fed 3456 µm crumbles. However, these broilers fed intermediate particle sizes did not result in a similar 7-14 d BW gain as broilers receiving 3736 µm crumbles. These differences in 7-14 d BW gain may be attributed to broilers presented crumbles of 1174 or 1423 µm having a decreased consumption of feed from 7-14 d in comparison to other treatments; with the exception 3456 µm, which consumed an intermediate amount of feed (P=0.002, Table 3.7). Broilers receiving crumbles of a larger average particle size (2800, 3456, or 3736 µm) resulted in improved 0-14 d BW gain and d 14 ending BW by approximately 30 g as compared to broilers fed 1174 or 1423 µm (P<0.0001, Table 3.7). Broilers fed crumbles of intermediate particle size (1883, 2049, or 2257 µm) performed similar to those fed 3456 µm crumbles. However, birds fed these intermediate size crumbles did perform similar in regards to 0-14 d BW gain or d 14 ending BW to that of broilers receiving 3736 µm crumbles. Similar to FCR results, the current experiment suggests that crumble particle size presented from 7-14 d may be more important to improve 0-14 BW gain than particle size presented from 0-7 d. This improvement may be partially influenced by FI; however this cannot be confirmed due to similarity in feed consumption of treatments receiving crumbles of 1883 µm or greater.

Probabilities associated with regression are located in Table 3.8. While 0-7 d and 7-14 d P-values are included in tabular form for the reader's reference, only 0-14 d P-values will discussed due to interest of space and similarity of relationships. Similar to experiment 1, a linear relationship for 0-14 d FCR was demonstrated with improved feed conversion as crumble particle size increased ($P<0.0001$, $R^2=0.945$, Table 3.8). Similarly to linear relationships demonstrated for 0-14 d FCR, a linear relationship for 0-14 d BW gain ($P=0.002$, $R^2=0.837$, Table 3.8) and d 14 ending BW ($P=0.002$, $R^2=0.836$, Table 3.8) demonstrated that BW gain increased as birds were fed crumbles of an increased particle size. Feed intake demonstrated a quadratic relationship in which feed consumption increased as birds were fed increased particle size until 2800 µm ($P=0.033$, $R^2=0.754$, Table 3.8).

Conversely to experiment 1, benefits were apparent for performance variables beyond FCR (e.g. ending BW and BW gain). Results from experiment 2 demonstrated improvements of approximately 30 g for 0-14 d BW gain and d 14 ending BW; with a 0.03 improvement in FCR. These findings are in agreement with previous research examining the effects of FF in the starter diet [14, 23-25]. Perhaps the broader range of crumble particle sizes (and larger particle sizes) in experiment 2 provided greater opportunity to observe these benefits. However, the first five treatments utilized in Experiment 2 (1174 - 2257 µm) were encompassed in experiment 1 and demonstrated differences in d 14 ending BW and 0-14 d BW gain for experiment 2; which were not present in experiment 1. Therefore, the magnitude of the effects of average crumble particle size on 0-14 d chick performance may have been further elucidated by environmental conditions. While experiments 1 and 2 were conducted in the same

research barn and utilized the same methodologies, experiment 1 was conducted in the winter whereas experiment 2 was conducted in the early spring.

These data obtained from experiment 2 suggest that providing an average crumble particle size of 2257 µm or greater improves 0-14 d FCR by approximately 0.03. Additionally, providing a crumble of 2800 µm may improve 0-14 d BW gain by approximately 30 g. However, as demonstrated in experiment 1, linear regression for 0-14 d FCR suggests that the optimal crumble particle size may be larger than 3736 µm. This is an extremely large average "crumble" particle size and is close to classification of a "pellet" (i.e. 4000 µm) utilizing the classification outlined by Glover and cohorts and Lemons and Moritz [14, 15]. Furthermore, based on descriptive data in Table 3.2, broilers provided the largest average particle size treatment of 3736 µm actually received 76% pellets.

While these data are contrary to the current belief, perhaps broilers are able to consume feed of larger particle sizes earlier than originally conceived. The authors speculate broiler chicks may be able to self-adapt to larger crumble particle sizes as the starter phase progresses due to the deviations in the particle sizes presented. For experiment 2, employing logarithmic functions [45] demonstrated 67% of particles ranged from 1364-5741, 1901-6295, and 2182-6382 µm for broilers receiving 2800, 3456, or 3736 µm crumbled treatments, respectively. Therefore, it is plausible that broiler chicks actively select smaller particle sizes during the early stages of the starter phase, then transition themselves with the presence of larger particle sizes allowing for associated improvements in d 0-14 performance. However, this may not be the case for each genetic strain due to differences in quantitative genetics. The current study only utilized Ross x

Ross 708 male broilers; therefore, this claim cannot be confirmed for all genetic strains. Previously outlined research has demonstrated differences in the magnitude of performance benefits as a result of improving FF in the starter phase, dependent on the genetic strain utilized [14, 15, 23-25]. However, the responses of FF due to genetic strain are not completely known. Sellers and cohorts demonstrated interactions between FF and genetic strain for d 43 pectoralis major yield using Ross 708 and Cobb 500 male broilers [16]. While performance interactions were not apparent for Sellers and cohorts, it does demonstrate the potential for genetic strain to influence responses to FF. Thus, future work relating to starter particle size should include different genetic strains.

Overall Summary

The current study supports feeding increased crumble particle size; although, the optimal particle may differ based on the desired performance metric. However, gastrointestinal morphology data for both experiments did not suggest a mechanism(s) of action for improvements in performance. Based on the findings of experiment 2, feeding crumbles of 2800, 3456, or 3736 µm yields a 30 g improvement in d 14 ending BW and 0-14 d BW gain. In regards to FCR, experiment 1 suggests feeding an average crumble particle size of 1760 or 2172 µm, whereas experiment 2 suggests feeding a crumble 2257 to 3736 µm for a 0.03 improvement in 0-14 d FCR. However, due to linear relationships for regression and no performance detriment associated with crumbles of a large particle size (e.g. 3736 µm), the primary objective of determining the optimal crumble particle size was not achieved in either experiment. Due to the improvements in performance associated with feeding chicks a crumble particle size of 3736 µm (76% pellets), we believe broiler chicks may be able to consume pellets at an earlier age (≤14 d) than

originally thought. This could have significant economic implications due to reductions in energy costs associated with the crumbling of pellets and improvements in feed throughput (due to not exceeding the crumbler capacity). However, further research must explore this possibility for determination of feasibility in a commercial setting.

Conclusions and Applications

1. Day 0-14 BW gain and d 14 ending BW may be maximized by feeding crumbles 2800 µm or greater.
2. These data suggests feeding crumbles of 1760 or 2172 µm (Experiment 1) or crumbles greater than 2257 µm up to 3736 µm (Experiment 2) for improvements in 0-14 d FCR of approximately 0.03.
3. Future research is warranted to determine the potential to feed broiler chicks pelleted diets, due to improvements associated with feeding the 3736 µm diet which was compromised of 76% pellets, as well as to determine respective differences in 0-14 d starter performance utilizing different genetic strains.
4. Gastrointestinal morphology was impacted by crumble particle size. However, this impact was minor and not consistent between experiments. Therefore, the resulting mechanism (s) of action is unclear.

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Table 3.1 Diet composition of the starter diet fed to Ross x Ross 708 male broilers from d 0-14 in Experiments 1 and 2.

Starter Diet (0-14d)	
Ingredient	Inclusion, (%)
Corn	47.835
Soybean Meal (48% CP)	40.289
Soybean Oil	3.498
Corn Dried Distillers Grains and Solubles	3.000
Meat and Bone Meal (50% CP)	2.000
Dicalcium Phosphate	0.919
Limestone	0.848
DL-Methionine	0.328
Sodium Chloride	0.325
Titanium Dioxide	0.300
Vitamin and Trace Mineral Premix[1]	0.273
Sodium Bicarbonate	0.212
L- Lysine HCl	0.086
L-Threonine	0.032
Selenium Premix (0.06%)	0.021
Phytase	0.020
Choline Chloride (60%)	0.014
Calculated Nutrients	
Metabolizable Energy (kcal/kg)	3000.000
Crude Protein (%)	25.728
Digestible Lysine (%)	1.280
Digestible TSAA (%)	0.973
Digestible Threonine (%)	0.832
Calcium (%)	0.810
Available Phosphorus (%)	0.330
Sodium (%)	0.220

[1]Supplied per kg of diet: manganese, 0.02%; zinc 0.02%; iron, 0.01%; copper, 0.0025%; iodine, 0.0003%; selenium, 0.00003%; folic acid, 0.69mg; choline, 386mg' riboflavin, 6.61mg; biotin, 0.03mg; vitamin B6, 1.38mg; niacin, 27.56mg; pantothenic acid, 6.61mg; thiamine, 2.20mg; manadione, 0.83mg; vitamin B12, 0.01mg; vitamin E, 16.53 IU; vitamin D3, 2133 ICU; vitamin A, 7716 IU.

Table 3.2 Descriptive feed form assessment data for treatments fed to Ross x Ross 708 male broilers from d 0-14 in Experiments 1 and 2.

Treatment	Experiment 1				Experiment 2						
	Average Production Rate[1] (tonne/h)	NHPT[2,3] (%)	Average Particle Size[4] (µm)	Standard Deviation (±)	Average Production Rate (tonne/h)	NHPT (%)	Average Particle Size (µm)	Standard Deviation (±)	Pellets[6] (%)	Crumbles[7] (%)	Fines[8] (%)
1	0.933	59.97	1202	1.93	0.841	84.34	1174	1.90	0	54.21	45.79
2			1335	1.96			1423	1.93	0.28	64.53	35.19
3			1675	1.93			1883	1.82	2.13	71.03	26.84
4			1760	2.01			2049	1.88	10.03	73.26	16.71
5			2172	1.99			2257	2.01	30.82	57.65	11.54
6	-		-	-			2800	2.05	67.12	23.06	9.82
7	-		-	-			3456	1.82	69.65	18.14	12.21
8	-		-	-			3736	1.71	76.05	15.17	8.78

[1]Determined measuring pellet volume post extrusion for a 60 s sampling period.
[2]NHPT=New Holmen Pellet Tester.
[3] Pellets were sifted through No. 5 American Society of Agricultural Engineers (ASAE) screen and 100 g of sifted pellets were placed in holding chamber, blown for 30 s by a jet of air, then weighed, giving a direct read of pellet survivability. Fines are removed during the blowing process.
[4]Determined using ASAE S319.2 in Tyler RO-TAP RX-29 for 10 min. processing period; performed in duplicate.
[6-8]Representative sample was hand sifted through column of ASAE #5 and #14 sieve column; [6]Pellets- Retained on #5 sieve, [7]Crumbles-Retained on #14 sieve, [8]Fines-Unretained feed.

Table 3.3 Experiment 1 comparisons of d 15 gastrointestinal morphology measurements and relative organ weight for Ross x Ross 708 male broilers fed starter diets varying in crumble particle size from d 0-14.

Crumble Particle Size[1]	Lengths (cm)			pH[2]		Relative Organ Weight[3,4](%)						
	Duodenum	Jejunum	Ileum	Gizzard	Ileum	Gizzard	Proventriculus	Pancreas	Duodenum	Jejunum	Ileum	Small Intestine[5]
1202 µm	24.900	47.286	42.063	2.171	5.360^{b}	2.551	0.599	0.404	1.590	2.466^{b}	1.746	5.736
1335µm	25.474	46.904	43.951	2.399	5.611^{a}	2.607	0.636	0.389	1.627	2.444^{b}	1.737	5.744
1675 µm	24.259	44.688	40.625	2.305	5.584^{a}	2.583	0.649	0.402	1.495	2.425^{b}	1.660	5.585
1760 µm	24.886	47.846	43.883	2.399	5.460^{ab}	2.459	0.636	0.391	1.528	2.603^{a}	1.748	5.890
2172 µm	25.188	46.375	41.375	2.239	5.569^{a}	2.479	0.631	0.402	1.541	2.465^{b}	1.672	5.654
ANOVA P-Value	0.312	0.524	0.137	0.470	0.004	0.196	0.161	0.840	0.196	0.039	0.258	0.181
SEM	0.403	1.357	1.097	0.105	0.051	0.051	0.014	0.011	0.041	0.043	0.036	0.090

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$).
[1]Treatments were created using one nutritionally common diet formulation that was pelleted (conditioned at 82°C) and ground using a crumbler adjusted to create the desired particle size for each treatment.
[2]pH measured before removal of digesta.
[3]Digesta was emptied prior to recording organ weight.
[4]Individual bird weights were taken before euthanasia to allow for determination of relative organ weight using the following equation: (Organ Weight/ BW) x 100).
[5]Summation of Duodenum, Jejunum, and Ileum were compared.

Table 3.4 Experiment 2 comparisons of d 15 gastrointestinal morphology measurements and relative organ weight for Ross x Ross 708 male broilers fed starter diets varying in crumble particle size from d 0-14.

Crumble Particle Size[1]	Lengths (cm)			pH[2]		Relative Organ Weight[3,4](%)						
	Duodenum	Jejunum	Ileum	Gizzard	Ileum	Gizzard	Proventriculus	Pancreas	Duodenum	Jejunum	Ileum	Small Intestine[5]
1174 µm	24.500	54.167	55.167	2.966	5.660	2.532	0.552	0.358	1.343	2.157	1.533	5.063
1423 µm	24.955	54.125	54.083	2.838	5.633	2.459	0.560	0.357	1.346	2.100	1.505	4.946
1883 µm	25.667	55.034	54.583	2.821	5.656	2.604	0.549	0.353	1.343	2.080	1.548	4.973
2049 µm	25.135	54.500	54.866	2.863	5.585	2.508	0.566	0.336	1.327	2.066	1.481	4.947
2257 µm	25.083	53.593	52.871	2.790	5.514	2.477	0.563	0.355	1.332	2.121	1.513	4.991
2800 µm	24.250	54.583	54.600	2.892	5.612	2.517	0.567	0.350	1.300	2.013	1.521	4.863
3456 µm	24.833	54.833	54.583	2.988	5.608	2.471	0.525	0.343	1.347	2.172	1.538	5.065
3736 µm	25.000	52.093	53.833	2.779	5.656	2.419	0.549	0.345	1.265	1.957	1.463	4.667
ANOVA P-Value	0.630	0.846	0.968	0.816	0.779	0.862	0.748	0.948	0.717	0.052	0.914	0.247
SEM	0.499	1.320	1.374	0.106	0.064	0.083	0.017	0.014	0.036	0.050	0.048	0.113

[1]Treatments were created using one nutritionally common diet formulation that was pelleted (conditioned at 82°C) and ground using a crumbler adjusted to create the desired particle size for each treatment.
[2]pH measured before removal of digesta.
[3]Digesta was emptied prior to recording organ weight.
[4]Individual bird weights were taken before euthanasia to allow for determination of relative organ weight using the following equation: (Organ Weight/ BW) x 100).
[5]Summation of Duodenum, Jejunum, and Ileum were compared.

Table 3.5 Experiment 1 comparisons of Ross x Ross 708 male broiler performance when fed starter diets varying in crumble particle size from d 0-14.

Crumble Particle Size[1]	d 0 Starting Bird Weight[2] (kg)	Feed Intake/Bird (kg)	BW Gain/bird (kg)	14 d Ending BW (kg)	FCR	Mortality (%)	d 14 CV of Ending Bird Weight (%)
1202 µm	0.043	0.473	0.356	0.399	1.324[a]	1.250	9.757
1335µm	0.043	0.476	0.361	0.404	1.312[a]	1.563	10.052
1675 µm	0.043	0.468	0.360	0.403	1.307[a]	0.938	10.569
1760 µm	0.043	0.478	0.366	0.409	1.287[b]	0.938	10.709
2172 µm	0.043	0.473	0.366	0.409	1.287[b]	1.563	11.139
ANOVA P-Value	0.809	0.266	0.155	0.158	0.0001	0.894	0.193
SEM	$3.329*10^{-5}$	0.003	0.003	0.003	0.006	0.598	0.436

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$).
[1]Treatments were created using one nutritionally common diet formulation that was pelleted (conditioned at 82°C) and ground using a crumbler adjusted to create the desired particle size for each treatment.
[2]Each pen consisted of 20 birds during placement.

Table 3.6 Experiment 1 regression probability values when using treatment means for Ross x Ross 708 male broiler performance when fed starter diets varying in crumble particle size from d 0-14.

Type of Regression	Feed Intake/Bird (kg)		BW Gain/bird (kg)		d 14 Ending BW (kg)		FCR[1]		Mortality (%)		d 14 CV of Ending BW[2] (%)	
	P-Value	R^2	P-Value	R^2	P-Value	R^2	P-Value	R^2	P-Value	R^2	P-Value	R^2
Linear	0.885	-	0.114	-	0.112	-	0.034	0.822	0.940	-	0.001	0.982
Quadratic	0.920	-	0.597	-	0.609	-	0.519	-	0.237	-	0.022	0.999
Cubic	0.966	-	0.877	-	0.878	-	0.909	-	0.205	-	0.652	-

[1]Significant FCR equation: $y = -4E\text{-}05x + 1.3651$.
[2]Significant d 14 CV of Ending BW equation: $y = -6E\text{-}07x^2 + 0.0035x + 6.4942$.

Table 3.7 Experiment 2 comparisons of Ross x Ross 708 male broiler performance when fed starter diets varying in crumble particle size from d 0-14.

Crumble Particle Size[1]	Starting Bird Weight[2] (kg)	Feed Intake/Bird (kg)			BW Gain/bird (kg)			Ending BW (kg)		FCR			Mortality (%)			CV of Ending BW (%)	
	d 0	0-7 d	7-14 d	0-14 d	0-7 d	7-14 d	0-14 d	d 7	d 14	0-7 d	7-14 d	0-14 d	0-7 d	7-14 d	0-14 d	d 7	d 14
1174 µm	0.041	0.147	0.370^{c}	0.518^{c}	0.128^{c}	0.302^{d}	0.429^{d}	0.169^{d}	0.471^{e}	1.135^{a}	1.216^{ab}	1.191^{ab}	2.083	1.272	3.333	10.089	9.791
1423 µm	0.041	0.149	0.371^{c}	0.520^{c}	0.129^{c}	0.303^{d}	0.432^{d}	0.171^{cd}	0.474^{de}	1.133^{a}	1.220^{ab}	1.197^{a}	3.333	0.855	4.167	9.429	8.511
1883 µm	0.041	0.149	0.382^{ab}	0.532^{ab}	0.134^{b}	0.314^{bc}	0.447^{c}	0.175^{bc}	0.489^{c}	1.107^{ab}	1.215^{ab}	1.181^{abc}	1.667	3.355	5.000	9.905	9.435
2049 µm	0.041	0.149	0.381^{ab}	0.530^{abc}	0.135^{ab}	0.308^{cd}	0.444^{c}	0.177^{ab}	0.485^{cd}	1.083^{b}	1.227^{a}	1.178^{bc}	5.000	3.645	8.333	10.034	9.934
2257 µm	0.041	0.150	0.383^{ab}	0.532^{ab}	0.134^{ab}	0.316^{bc}	0.450^{bc}	0.176^{abc}	0.492^{bc}	1.098^{b}	1.208^{b}	1.173^{cd}	3.333	6.880	10.000	10.573	10.828
2800 µm	0.041	0.150	0.389^{a}	0.539^{a}	0.139^{a}	0.322^{ab}	0.461^{ab}	0.180^{a}	0.502^{ab}	1.085^{b}	1.206^{bc}	1.168^{cd}	0.833	3.772	4.583	10.640	9.606
3456 µm	0.041	0.151	0.378^{bc}	0.527^{bc}	0.138^{ab}	0.318^{ab}	0.455^{abc}	0.179^{ab}	0.496^{abc}	1.095^{b}	1.182^{d}	1.156^{d}	2.083	0.907	2.917	10.124	9.457
3736 µm	0.041	0.149	0.384^{ab}	0.533^{ab}	0.138^{ab}	0.327^{a}	0.465^{a}	0.179^{ab}	0.507^{a}	1.083^{b}	1.188^{cd}	1.157^{d}	2.083	5.180	7.083	10.288	9.358
ANOVA P-Value	0.090	0.846	0.002	0.007	<0.001	<0.001	<0.001	<0.001	<0.001	0.004	<0.001	<0.001	0.382	0.081	0.178	0.884	0.526
SEM	4.886 * 10^{-5}	0.002	0.003	0.004	0.002	0.003	0.004	0.002	0.004	0.012	0.007	0.006	1.237	1.564	2.060	0.596	0.705

[a-d]Means within a column not sharing a common superscript differ ($P \leq 0.05$).

[1]Treatments were created using one nutritionally common diet formulation that was pelleted (conditioned at 82°C) and ground using a crumbler adjusted to create the desired particle size for each treatment.

[2]Each pen consisted of 20 birds during placement.

Table 3.8 Experiment 2 regression probability values when using treatment means for Ross x Ross 708 male broiler performance when fed starter diets varying in crumble particle size from d 0-14.

Type of Regression		Linear		Quadratic		Cubic	
Variable Measured	Day Range	P-Value[1]	R^2	P-Value	R^2	P-Value	R^2
Feed Intake/ bird (kg)	0-7 d[1]	0.092	-	0.044	0.754	0.955	-
	7-14 d[2]	0.109	-	0.033	0.768	0.816	-
	0-14 d[3]	0.134	-	0.033	0.754	0.940	-
BW gain/ bird (kg)	0-7 d[4]	0.004	0.784	0.005	0.962	0.749	-
	7-14 d[5]	0.003	0.804	0.309	-	0.812	-
	0-14 d[6]	0.002	0.837	0.101	-	0.734	-
Ending BW[8,9] (kg)	d 7[7]	0.003	0.788	0.004	0.967	0.751	-
	d 14[8]	0.002	0.836	0.100	-	0.736	-
FCR[10-12]	0-7 d[9]	0.027	0.586	0.037	0.841	0.541	-
	7-14 d[10]	0.006	0.743	0.173	-	0.319	-
	0-14 d[11]	<0.0001	0.945	0.436	-	0.467	-
Mortality (%)	0-7 d	0.466	-	0.683	-	0.315	-
	7-14 d	0.448	-	0.251	-	0.394	-
	0-14 d	0.808	-	0.268	-	0.211	-
CV of Ending BW (%)	d 7	0.218	-	0.285	-	0.280	-
	d 14	0.945	-	0.274	-	0.910	-

[1]Significant 0-7d Feed Intake/ bird equation: $y= -1E-09x^2 + 6E - 06x + 0.1413$.
[2]Significant 7-14 d Feed Intake/ bird equation: $y= -6E-09x^2 + 3E - 05x + 0.3375$.
[3]Significant 0-14 d Feed Intake/ bird equation: $y= -6E-09x^2 + 4E - 05x + 0.4843$.
[4]Significant 0-7 d BW gain/ bird equation: $y= -3E-09x^2 + 2E - 05x + 0.1107$.
[5]Significant 7-14 d BW gain/ bird equation: $y= 8E - 06x + 0.2939$.
[6]Significant 0-14 d BW gain/ bird equation: $y= 1E - 05x + 0.4186$.
[7]Significant d 7 ending BW equation: $y= -3E-09\ x^2 + 2E - 05x + 0.1531$.
[8]Significant d 14 ending BW equation: $y= 1E - 05x + 0.4601$.
[9]Significant 0-7 d FCR equation: $y= 2E-08\ x^2\ 1E - 04x + 1.2280$.
[10]Significant 7-14 d FCR equation: $y= -1E - 05x + 1.2417$.
[11] Significant 0-14 d FCR equation: $y= -2E - 05x + 1.2118$.

CHAPTER IV

EFFECTS OF FEEDING TWO BROILER STRAINS FROM D 0-18 VARIED FEED FORM (CRUMBLES OR PELLETS) OF VARIED QUALITIES (LOW, MEDIUM, OR HIGH) ON STARTER PERFORMANCE (D 0-18) AND EARLY GASTROINTESTINAL DEVELOPMENT, AS WELL AS D 62 PERFORMANCE AND D 63 PROCESSING

Summary

Previous research in our laboratory demonstrated that feeding an average crumble particle size of 2200 to 3736 µm improved starter performance (d 0-14). These data suggested that broiler chicks may be able to consume pellets during the starter phase without detrimental effects on performance. Therefore, the objective of the current study was to evaluate the effects of three large crumble particle sizes and pellets of three different intact pellet (IP) percentages presented during the starter growth phase (d 0-18) on starter performance utilizing two different genetic strains [GS; high yielding (HY) or fast growing (FG)]. Additionally, gastrointestinal development during the starter phase was examined to explain associated mechanism(s) of action for perceived performance improvements. Lastly, additional research from our laboratory has determined that starter feed form (FF) influenced overall performance; therefore the potential for carryover effects in overall performance and processing characteristics, due to FF and feed quality

(FQ) presented during the starter growth phase, was examined in the current study by feeding common diets for the remainder of the grow out. Feed form and FQ interacted for d 0-18 BW ($P<0.05$). Birds fed crumbles had the highest weight regardless of crumble FQ; birds fed IP achieved larger weights when FQ was highest, similar to birds fed crumbles. Gastrointestinal measurements suggested feeding the FF of pellets or High FQ reduced small intestinal lengths and relative weight, respectively, at early stages during the starter phase; with consistent effects being lost later during the starter phase. Examining the carryover effects, 0-32 d FCR was improved with providing High FQ crumbles (3388 μm). Overall data (d 0-62) demonstrated no significant differences for measured performance variables. As expected, three-way interactions between GS x FF x FQ were apparent demonstrating differences in pectoralis major yields dependent on the FF and FQ presented from d 0-18 for each GS. In particular, HY demonstrated improved pectoralis major yields if fed Low FQ crumbles or High FQ pellets; whereas FG broilers demonstrated similar yields regardless of FF or FQ. These data demonstrate that the relationship between FQ, FF, and GS is complex, suggesting that the length of the growout is important when determining which FQ and FF to present in the starter growth phase.

Description of the Problem

It is well appreciated that improvements in FF (providing higher percentages of IP) result in improved broiler performance [1-11]. However, research pertaining to the optimal crumble particle size of feed in the starter growth phase is particularly void. Due to the ever-increasing improvements in quantitative genetics [12], the starter growth

phase continues to represent an increasing proportion of a broiler's lifecycle [13, 14]. One area of interest during this growth phase is to facilitate feed intake initiation to ensure chicks are successfully transitioning to receiving nutrients via complete feed rather than the egg yolk supply [14]. The development of the small intestine is occurring rapidly post hatch, but digestion and absorption of nutrients is limited [15]; thus making initiation of feed intake critical. In an effort to stimulate feed intake, providing broiler chicks feed in a crumble form during the starter growth phase is common practice. However, the optimal average particle size to provide during the starter phase is currently unknown and warrants exploration.

It has been accepted that broilers consume feed based on beak capacity [16-18]. However, the biomechanics of particle size selection is extremely complex. Mechanoreceptors are present within the beak of broilers, allowing for selection of the appropriate particle size based on beak capacity [16, 17]. One such study examining the feeding behavior in young broiler chicks demonstrated that two-thirds of pecks did not result in the apprehension of feed particles for consumption [19]. Previous research has demonstrated that broilers prefer a larger particle size, with this preference increasing as broilers age [18, 21, 22]. Recently, Huang and De Beer confirmed that broiler chicks (unidentified strain) demonstrated preferences for distinct crumble particle sizes, with the preference for a larger particle size as broilers increased with age [23]. One interesting finding from this work was that birds would reject fine particles (< 860 μm) as early as 3 days post hatch. Moreover, performance was improved at the end of the starter period (d 9) when broilers consumed their preferred crumble particle size of 2180-3180 μm. These findings were intriguing, as the crumble particle size implemented during these trials was

much greater than typically utilized in Mississippi's commercial industry based on integrator sampling (unpublished data).

Due to the limited knowledge regarding the optimal particle size of crumbles for maximized starter growth performance, two experiments were conducted in our laboratory [24]. In both experiments, nutritionally common diets differing only in crumble particle size were presented to Ross x Ross 708 male broilers during the starter period (d 0-14) to determine the impacts on starter performance. Experiment 1 provided five different crumble particle sizes ranging from 1202-2172 µm; whereas experiment 2 provided eight different crumble particle sizes ranging from 1174-3736 µm. Experiment 1 demonstrated improvements in d 0-14 FCR of 0.03 when crumbles of 1760 or 2172 µm were fed. However, linear regression suggested that crumbles greater than 2172 µm may be advantageous for further improvements in d 0-14 FCR thus leading to experiment 2. Experiment 2 demonstrated improvements in d 0-14 FCR, with the greatest improvements (0.03) being associated with broilers receiving crumbles of 3456 or 3736 µm. Additionally, improvements in d 0-14 BW and BW gain were observed for broilers receiving crumbles greater than 2800 µm.

These findings suggested that broiler chicks were able to consume crumbles of a larger particle size than originally conceived with associated improvements in starter performance. Additionally, due to the absence of detriment in performance associated with large crumble particle sizes, this suggested broilers may be able to consume pellets in the starter phase. However, the impacts on overall performance and processing characteristics due to FF presented in the starter growth phase were unable to be answered and warranted further research.

Previous research has suggested strong correlations of d 7 BW on market weight at slaughter [13]. Therefore, it is plausible that improvements in the starter growth phase may translate to improved overall performance and processing characteristics. One such study examined the potential for benefits due to improved FF presented during the starter phase to improve overall performance and processing characteristics [25]. Although improvements in the starter phase were observed by providing improved FF (micropellets or crumbles), these associated improvements were not observed at the end of the growth phase, which they speculated were due to compensatory growth [25].

Recent research in our laboratory demonstrated that FF presented in the starter growth phase interacted with FF presented in subsequent growth phases to influence overall broiler performance and processing characteristics [26]. These differences may be partially explained by differences in GS used in research conducted by Cerrate and cohorts [25] in comparison to that in our laboratory [26], implementing Cobb 500 vs Ross 708 male broilers, respectively. Due to selection by parent genetic companies for desired traits, it is plausible that this intense genetic selection has resulted in higher variation associated with offspring [27-29]. Therefore, broilers of different GS may also exhibit differences in observed performance metrics due to FF, and the FQ of that associated FF. One such study demonstrated broilers of a HY strain were more sensitive to changes in FF presented during the finishing phase (d 28-42), as compared to those of a FG strain, for d 43 pectoralis major yield; however, no apparent differences were not observed for performance [11].

Therefore, it is likely that the impacts of starter FF on overall performance and processing characteristics is a complex interaction between a multitude of factors such as:

FF, FQ, and GS. Therefore, the primary objective of the current study was to evaluate the effects of feeding two FF (varying crumble particle sizes and IP percentages) during the starter growth phase (d 0-18) on starter performance using two commonly implemented GS (HY or FG). These FF were fed as one of three FQ (Low, Medium, or High). Additionally, the potential of a carryover effect on overall performance due to FF and FQ fed in the starter phase was also examined. Lastly, in an effort to explain expected performance differences due to FF and FQ in the starter phase, gastrointestinal measurements were examined throughout the starter growth phase.

Materials and Methods

The current study utilized a 2 x 2 x 3 factorial arrangement of treatments within a randomized complete block design. The main effects consisted of two GS (HY or FG), two FF (pellet or crumbles), and three FQ (Low, Medium, or High) for each FF. A treatment structure is outlined in Table 4.1. All methodologies were compliant with the Mississippi State University Institutional Animal Care and Use Committee (IACUC #17-401). During the starter (d 0-18) growth phase, experimental diets (differing only in FF and FQ) were presented; whereas common diets were presented for the remainder of the performance trial. Methodology in this section will primarily focus on the starter growth phase, with any distinctions in methodology regarding subsequent growth phases being noted.

Feed Manufacture

Diet preparation

Feed for each growth phase was manufactured at a commercial integrator's feed mill utilizing the standard operating procedures (SOP) for that respective mill. Following manufacture, all diets were loaded in bulk transport bags (1 tonne capacity) and transported to the Mississippi State University poultry research unit for the live performance portion of the experiment. Diets utilized in the current study were commercial formulations and thus, proprietary; however they were all-vegetable (corn-soybean meal based) and formulated for each respective growth phase to commercial broiler recommendations [30]. Specific diet formulations are proprietary and will not be shared; however, their proximate analysis can be located in Table 4.2.

At the commercial mill for the starter period (d 0-18), two nutritionally common batches were made prior to further modification for the creation of treatments differing in FQ for each respective FF. This was performed in effort to prevent the potential of confounding effects due to differing basal batches. Feed in subsequent growth phases (>18 d) was manufactured without further modification to pellets prior to feeding to determine the potential of carryover effects due FF and FQ presented in the starter growth phase. Diets for all growth phases were steam conditioned for 20 s at 88 °C and extruded through a 4.37 mm diameter pellet die with an effective length of 25 mm; driven by a 500-horsepower California Pellet Mill [31]. Both FF of pellets and crumbles were produced at production rate of ~ 41 tonne/h.

Starter Phase Treatment Creation

For the starter growth phase, two different FF (crumbles or pellets) were fed as one of three assigned FQ (Low, Medium, or High) to create six distinct dietary treatments. Pellets were manufactured first, followed by the creation of crumbles. Pelleted diets were manufactured without any further modification at the commercial mill. A portion of the pelleted diet was ground via hammer mill for the creation of "fines" at Mississippi State University [32]. Unmodified pelleted diets were determined to contain approximately 85% intact pellets (IP) utilizing an American Society of Agricultural Engineers #5 sieve. For the creation of each FQ for pellets, "fines" were added to the original pelleted diet and hand mixed, prior to feeding individual pens, in differing proportions to the create the Low (40% IP), Medium (60% IP) and High (80% IP) FQ.

For the FF of crumbles, Low and High FQ was created by adjusting the gap width of a double-stage crumbler [33] at the commercial mill. This adjustment was performed utilizing fabricated metal shims to manipulate the automated roll adjustment to the desired gap width. This desired gap width was based on preliminary sampling and modifications prior to the experimental manufacture (data not presented). A 50:50 ratio of Low and High crumbles was hand-mixed prior to feeding individual pens for the creation of the Medium FQ. Representative samples of each FQ were collected for the determination of average particle size and particle size standard deviation using Tyler RO-TAP RX 29 [34] for a 10 minute processing period and performed in duplicate [35]. Particle size determination was also performed for each FQ of pelleted treatments after their creation using hand mixing. In addition to particle size determination, percent

survivability of pellets was performed using a New Holmen Pellet Tester for a 30 sec processing period (performed in duplicate) [36]. Descriptive data from these analyses can be located in Table 4.3.

Live Performance

The current study employed two common GS, [high yielding (HY) [37] and fast-growing (FG) [38]. A total of 1,404 straight-run broilers for each GS were obtained from two commercial hatcheries [39, 40] and equally (randomly) allocated to 108 pens (1.22 m x 1.52 m; 9 pens/treatment) based on GS. In an effort to prevent confounding effects due to age of parent breeding stock, chicks of both GS were sourced from parent stock of a similar age range (35 or 36 weeks). All broilers were reared using similar environmental recommendations in pens containing used litter that had been top-dressed with pine shavings [41]. Broilers were offered feed for *ad libitum* consumption on feed trays from 0-10 d and transitioned to tube feeders on d 10. From d 0-7, feed would be added to feed trays when the majority of residual feed was consumed. Broilers and tube feeders were individually weighed on d 7, 10, 14, and 18 for determination of performance variables. Performance variables measured included: feed intake/bird (FI), body weight gain/bird (BWG), ending BW, mortality corrected FCR, average mortality, and pen CV of ending BW. Following the starter growth phase, broilers and tube feeders were individually weighed at the end of each growth phase (d 32, 46, and 62) for determination of performance variables.

Gastrointestinal Measurements

On d 3, 5, 7, 10, 14, and 18, one bird per pen was randomly selected for gastrointestinal morphology measurements (9 replications per treatment/day). Broilers were euthanized via CO_2 asphyxiation, individually weighed, and respective organs were excised. Variables measured included lengths of the small intestine sections (duodenum, jejunum, and ileum) as well as the empty weights of the gizzard, proventriculus, pancreas, duodenum, jejunum, and ileum for determination relative organ weight (relative to broiler BW). Additionally, crop fill contents and remnant yolk sacks were removed and weighed. Crop fill contents were collected and moisture was removed by placing individual samples in a drying oven for 16 h at 105°C [42]. The pH of the gizzard and terminal ileum contents was determined utilizing a pH probe [43] prior to removal of the digesta for weighing of organs to occur.

Processing

Following the d 62 weigh day, two broilers of each sex per pen (n=432) were randomly tagged for determination of d 63 processing characteristics. All broilers were processed at the Mississippi State University pilot processing facility. Simultaneously during processing, hot carcass and abdominal fat pads were individually weighed and recorded. Hot carcasses were subsequently submerged in an ice bath (~ 3 h) until deboning. Carcasses were individually deboned by trained personnel and weighed to determine boneless, skinless pectoralis major, pectoralis minor, thigh, drumstick, and wing weight. Weights for individual parts, and total pectoralis, were then placed on a yield basis relative to d 62 BW and d 63 hot carcass weight for statistical analysis.

Additionally, wooden breast severity was determined for individual breast fillets by one trained panelist [44].

Statistical Analysis

All variables were analyzed in the aforementioned 2 x 2 x 3 factorial arrangement within a randomized complete block design using two-way ANOVA considering the main effects and interactions of GS (HY or FG), FF (Crumbles or Pellets), and FQ (Low, Medium, or High). The experimental unit was 1 pen containing 26 straight-run broilers of each GS. Each treatment was replicated 9 times and blocks were arranged by locations of pens within the house. All variables were analyzed using the GLM procedure of SAS [45], with significant treatment means ($P<0.05$) being separated using Fisher's protected LSD multiple comparison test. Significant differences were indicated by utilizing letter superscripts to denote differences among treatment means. Additionally, significant interactions between main effects for gastrointestinal measurement variables were further analyzed utilizing the correlation procedures (PROC CORR) in SAS to examine relationships relative to BW, BW gain, FI and FCR.

Results and Discussion

Although significance was demonstrated for the main effect of GS on performance, processing, and gastrointestinal measurement variables, marginal means will not be presented in tabular form (probability values are presented for reference in performance and processing tables). This is due to the objective of this trial being the determination of the interactive relationships of FF and FQ when presented to two commonly used GS; not to solely compare GS performance. Additionally, terms Low,

Medium and High will be used when discussing FQ effects, whereas the actual crumble particle size or IP percentage will be presented when discussing interactions between FF x FQ or GS x FF x FQ.

Gastrointestinal Measurements

Due to the experimental design and number of sampling days, interactions were present for different variables at days throughout the starter period. However, clear connections to observed performance metrics associated with these interactions were not apparent (data not presented). Moreover, significance was continually established for the main effects of FF and FQ throughout the starter period. Therefore, in the interest of space constraints and continuity, marginal means for the main effects of FF and FQ can be found for each sampling period in Tables 4.4 (d 3, 5, 7) and Tables 4.5 (d 10, 14, and 18). Additionally, in an effort to help explain performance differences, significant interactions were further analyzed utilizing correlation procedures to determine relationships relative to BW and BW gain (d 3, 5, 7, 10, 14, and 18); as well as FI (d 7, 10, 14, and 18) and FCR (d 7, 10, 14, and 18). These resulting relationships can be located in Table 4.6.

Feed Form Effects

For the main effect of FF, significance was primarily established for lengths and relative weight of the small intestine sections, with the nature of the effects being dependent on the sampling day. Feeding broiler chicks pelleted diets resulted in a 1.09 cm reduction in ileum length at d 3 as compared to those fed crumbled diets (P=0.024, Table 4.4). A similar effect was demonstrated at d 7 for jejunum length with broiler

chicks receiving pelleted diets having a 1.15 cm reduction in length compared to those fed crumbles (P=0.030, Table 4.4). Conversely, broilers receiving a pelleted diet resulted in 1.86 cm longer ileum length at d 18 compared to those fed crumbles (P=0.047, Table 4.5). Although differences in small intestine lengths were apparent, when placed on an relative organ weight basis, only significance was demonstrated at d 3 for relative jejunum weight with broiler chicks receiving pelleted diets having a 0.10 % higher relative weight (P=0.009, Table 4.4). While not significant, it is important to note trends in d 10 relative duodenum weight (P=0.098, Table 4.5) and d 18 relative jejunum weight (P=0.065, Table 4.5). Similar to d 3 relative jejunum weight, d 10 relative duodenum weight was increased for broilers receiving pelleted diets. Conversely, d 18 relative jejunum weight was increased with crumbled diets.

Examining the effects of FF on pH, significance was established at d 5 for both the gizzard (P=0.005, Table 4.4) and ileum (P=0.032, Table 4.4). In both cases, feeding pelleted diets resulted in a reduction of 0.153 and 0.270 for the gizzard and ileum in comparison to those fed crumbled diets, respectively. While significance was established at d 5 for both organs, significance was not established for either organ during other sampling periods. Although not significant, a trend for d 14 gizzard pH demonstrated a similar effect with broilers receiving pelleted diets having a reduction in pH (P=0.078, Table 4.5).

Feed Quality Effects

Similar to the main effect of FF, significance was primarily associated with the sections of the small intestine. At d 3, feeding broiler chicks High FQ (e.g. 3388 µm or

80% IP) resulted in a reduction of relative duodenum and jejunum weight compared to those receiving Low and Medium FQ, which performed similar (P=0.003, P=0.001, Table 4.4, respectively). Similar effects were demonstrated at d 5 for relative jejunum weight (P=0.036, Table 4.4) and relative ileum weight (P=0.042, Table 4.4). Broiler chicks receiving High or Medium FQ resulted in a ~0.161 % reduction in d 5 relative jejunum weight as compared to those fed Low FQ. Examining d 5 relative ileum weight, broilers receiving High FQ demonstrated a 0.169 % reduction as compared to those fed Low FQ; with broilers fed Medium FQ performing intermediate. Although not significant, a similar impact was demonstrated for d 5 relative duodenum weight with Low FQ having the highest relative duodenum weight (P=0.075, Table 4.4). At d 7, significance for relative organ weight was lost. However, a trend in ileum length demonstrated greater ileum lengths for broiler chicks receiving Low and Medium FQ as compared to those receiving High FQ (P=0.084, Table 4.4). Significance was reestablished at d 10 for relative ileum weight, with broilers receiving Low FQ having a higher relative weight as compared to those receiving High FQ; with Medium FQ performing intermediate (P=0.029, Table 4.5). In addition to d 10 relative ileum weight, d 10 duodenum length demonstrated a similar effect with Low FQ resulting in the largest length (P=0.032, Table 4.5). Significance for relative small intestine weights was not apparent for the remainder of the starter period (i.e. d 14 and d 18). However, d 18 ileum length and d 18 relative gizzard weight were significantly impacted by FQ presented. Regarding d 18 ileum length, feeding High FQ resulted in an increased ileum length of 2.93-3.22 cm as compared to those receiving Low or Medium FQ (P=0.004, Table 4.5).

However, feeding Low FQ resulted in a higher d 18 relative gizzard weight as compared to those receiving Medium or High FQ (P=0.018, Table 4.5).

Ileum pH was significantly impacted by FQ at d 3, 5, and 7. However, clear connections due to FQ were not apparent as resulting differences were influenced by sampling day. For d 3, feeding Medium FQ resulted in the highest ileum pH as compared to those receiving Low or High FQ (P=0.019, Table 4.4). At d 5, a similar impact was demonstrated, with High FQ then performing intermediate (P=0.037, Table 4.4). However, at d 7, opposite effects were demonstrated with birds fed Medium FQ demonstrating the lowest ileum pH as compared to those receiving Low or High FQ (P=0.009, Table 4.4). Ileum pH was not influenced at later sampling days. However, gizzard pH was influenced by FQ at d 14 with broilers receiving High FQ resulting in the highest pH compared to those receiving Low or Medium FQ (P=0.014, Table 4.5).

Conversely to FF, differences in measurements other than small intestine lengths and relative weight, as well as pH were observed; in particular, d 10 remnant yolk sack weight and d 18 crop fill. Feeding broiler chicks High FQ resulted in the highest yolk sack weight as compared to those receiving Medium FQ, with Low FQ performing intermediate (P=0.004, Table 4.5). For d 18 crop fill weight, feeding High FQ resulted in an improved crop fill of 0.749-0.941 g as compared to those receiving Low or Medium FQ (P=0.003, Table 4.5). Additionally, trends were observed for d 3 (P=0.068, Table 4.4) and d 10 (P=0.090, Table 4.5) relative pancreas weight and d 10 relative proventriculus weight (P=0.071, Table 4.5).

Correlation Analysis

As previously mentioned, interactions were present at different sampling days, likely due to the robust experimental design. However, clear connections, in regards to performance, were not apparent. Therefore, correlation was performed to obtain relationships of individual birds randomly chosen for sampling in comparison to pen performance metrics for each sampling day (Table 4.6.). It should be noted that because FI and FCR were not calculated at d 5 and 7, correlation analyses could not be performed for these performance metrics at d 5 and 7.

In general, correlation analysis demonstrated the majority of gastrointestinal measurements did not result in a significant relationship with observed performance variables. Of the significant relationships, the majority were associated with ending BW and BW gain. At d 5, ileum pH demonstrated a positive relationship with BW and BW gain (P=0.001, r=0.343; p=0.001, r=0.329, Table 4.6, respectively). However, relative organ weights demonstrated negative relationships (Table 4.6) as compared to BW and BW gain for d 7 relative gizzard weight (P=0.005, r=-0.272; P=0.007, r=-0.263), d 7 relative duodenum weight (P<0.001,r=-0.420; P<0.001, r=-0.424), and d 5 relative jejunum weight (P=0.012, r=-0.246; P=0.007, r=-0.263).

Examining the impacts of FI, the only relationship was demonstrated for d 10 ileum pH. This relationship suggests that increases in FI resulted in a higher ileum pH (P=0.019, r=0.230, Table 4.6). Looking at the relationships for FCR, d 18 crop fill, d 10 relative gizzard weight, and d 7 relative duodenum weight were impacted. Day 18 crop fill demonstrated a negative relationship with increases in crop fill weight resulting in reductions of FCR (P=0.038, r=-0.208). However, d 10 relative gizzard weight (P=0.025,

r=0.222) and d 7 relative duodenum weight (P=0.001, r=0.323) demonstrated positive relationships with increases in FCR as respective relative organ weight were increased (Table 4.6).

Gastrointestinal Measurement Discussion

Although the impact of ingredient particle size on gastrointestinal morphology have been extensively studied, the impact of FF on resulting gastrointestinal measurements are unknown. Of the limited available research, the primary focus has often been comparisons of pelleted diets vs unconditioned mash [46, 47]. The current study employed commonly implemented gastrointestinal measurements to help explain expected performance differences and provide information on the effects of complete diet particle size on gastrointestinal development.

The main effects of FF and FQ resulted in gastrointestinal measurement differences; with more differences being associated with the main effect of FQ. For both of these main effects, the sections of the small intestine were most often influenced. The current data in general demonstrates that feeding pelleted diets reduces intestinal length (section dependent on day; df3 and 7) and increased relative organ weights during the earlier stages of the broiler chick's lifecycle (i.e. d 3, 7, and 10). However, at the end of the starter period (d 18), opposite trends were observed for ileum length and relative jejunum weight. These reductions in small intestine length are supported by previous research demonstrating reduced lengths when comparing pelleted diets to unconditioned mash [46, 47].

Examining the main effect of FQ, providing broilers High FQ reduced relative small intestine weights and lengths during the early periods of the starter phase; similar to the effects observed for pellets. Once again, this relationship was reversed at d 18, with feeding High FQ resulting in increased ileum length. These inverse relationships may be better explained when examining the correlation results. In general, relative small intestine weight demonstrated a negative relationship with BW and BW gain and a positive relationship with FCR during early stages in the starter growth phase (i.e. d 5 and 7). Therefore, it is plausible that broilers are experiencing difficulty with consuming pellets at early stages in life, explaining the associated increases in relative small intestine weight. However, as appropriate physiological adaptions occur with age, reductions in relative organ weight coincide with improvements in performance. This suggested mechanism of action is supported by previous research demonstrating lower relative duodenum weight in birds fed "coarse" particle mash as compared to those fed "fine" mash [48].

In addition to small intestine lengths and relative weight, differences were observed for gizzard and ileum pH. Regarding gizzard pH, pelleted diets reduced gizzard pH at d 5 and tended to reduce pH at d 14. This could have extreme importance in today's broiler industry due to removal of antibiotics and anticoccidials, as it has been suggested that reduction of gizzard pH may be a viable strategy to reduce coccidiosis [49] and other pathogens [50]. Although ileum pH was influenced by FQ, consistent trends were not observed in the current study. It appears Medium FQ resulted in a greater ileal pH at d 3 and 5, while the opposite was demonstrated at d 7. These results were interesting as previous work has demonstrated reductions in intestinal pH as "fine"

particulate mash was presented to broilers; thus suggesting Low FQ would result in the lowest ileal pH [51]. However, the particle sizes utilized in the current trial were much larger than implemented in the aforementioned research, particularly that of unconditioned mash.

Overall, it appears that FF and FQ play an important role in gastrointestinal development, particularly in the sections of small intestine relative weight and length, as well as intestinal pH. However, clear mechanisms of action were not apparent as significance differed due to day and intestinal sections. However, these data suggest that reduction in relative organ weight may be associated with improved FF and FQ at early stages in a broiler's lifecycle. Though, future research is warranted to further explain the relationship with gastrointestinal development and broiler performance.

Live Performance

Due to the lack of significance for three-way interactions and space constraints, marginal means will not be presented (probability values are provided for reference). However, a significant three-way interaction was demonstrated for d 0-46 FCR (Figure 4.1). Additionally, as previously mentioned, marginal means for the main effect of GS will not be presented, but probability values are included for reference.

Starter Performance (d 0 -18)

Due to experimental treatments differing in FF and FQ being presented from d 0-18, performance variables were determined at four periods during the starter phase (d 7, 10, 14, and 18). Resulting performance metrics for d 7, 10, and 14 can be located in Table 4.7, whereas, performance metrics for the entirety of the starter period (d 0-18) are

located in Table 4.8. Due to the experimental design, significant interactions and trends were demonstrated at various points throughout the starter period. However, the majority of these significant interactions were present between the main effects of FF and FQ. Ending BW and BW gain were significantly impacted by the interactions of FF and FQ at d 10 and 14 ($P<0.05$, Table 4.7). Similar responses for d 10 BW ($P=0.032$, Table 4.7) and d 0-10 BW gain ($P=0.023$, Table 4.7) were observed with broilers receiving 2210 µm and 3008 µm crumbles resulting in an ~ 12 g improvement compared to those receiving 40% and 60% IP; with broilers receiving High FQ performing similar regardless of FF. Day 14 ending BW ($P=0.015$, Table 4.7) and d 0-14 BW gain ($P=0.014$, Table 4.7) demonstrated similar performance for all FQ receiving crumbles. However, broilers receiving 80% IP from d 0-14 demonstrated similar BW improvements as compared to those fed crumbled treatments, with an improvement in BW of ~ 20 g as compared to those receiving 40 or 60% IP. Similar responses were demonstrated for the whole starter period (d 0-18). Birds receiving the crumbled diets, regardless of FQ, resulted in similar performance, whereas BW and BW gain was improved as IP percentage increased, with birds fed 40% IP having the lowest BW and BW gain of all treatment combinations ($P=0.035$, $P=0.032$, respectively, Table 4.8).

Interactions between FF and FQ were not apparent for FCR as demonstrated for BW and BW gain. However, the main effect of FF consistently demonstrated improvements in FCR (ranging from 0.02-0.09) for d 0-7, 0-10, and 0-14 associated with broilers receiving crumbles ($P=0.001$, Table 4.7). These improvements translated to an associated 0.01 improvement in d 0-18 FCR for broilers receiving crumbled treatments. Feed quality also influenced d 0-14 FCR, with broilers receiving High FQ resulting in

0.016 reduction in d 0-14 FCR as compared to those receiving Low FQ; Medium FQ performed intermediate (P=0.042, Table 4.7). Perhaps, this reduction in d 0-14 FCR may be partially explained by differences observed for d 14-gizzard pH, which demonstrated a similar effect. Regardless, this resulted in 0.015 improvement in d 0-18 FCR for broilers receiving High FQ as compared to those receiving Low FQ; with Medium FQ performing intermediate (P=0.046, Table 4.8). Although significant FF x FQ interactions were not demonstrated for FCR at each sampling period, a trend for d 0-18 FCR revealed a similar response to that for d 18 ending BW and d 0-18 BW gain with reductions in FCR as IP increased(P=0.074, Table 4.8).

These aforementioned differences in FCR are likely influenced by FI. In particular, broilers receiving the FF of pellets demonstrated a higher feed consumption from d 0-7 and d 0-10 compared to broilers receiving crumbles (P=0.002, P=0.022, respectively, Table 4.7). Due to broilers receiving pelleted diets having a reduced BW during these periods and higher FI, increased FCR was to be expected. It is important to note that feed wastage was observed with pelleted treatments when broilers were presented feed on feed trays (d 0-10). Following the removal of feed trays, interactions between FF and FQ were present at d 0-14 and d 0-18. At d 0-14, broilers receiving 3388 µm crumbles demonstrated a reduced feed consumption in comparison to those receiving 3008 µm crumbles, with broilers receiving 2010 µm crumbles resulting in a similar consumption (P=0.005, Table 4.7). However, broilers receiving 80% IP resulted in the highest consumption, and broilers receiving 40 or 60% IP consumed a similar amount of feed to those given3388 µm crumbles. For d 0-18 FI, consumption was further separated among crumbled treatments with broilers receiving 3008 µm crumbles having the highest

FI in comparison to those receiving 3388 µm crumbles; broilers fed pellets demonstrated similar FI regardless of FQ (P=0.012, Table 4.8).

Although the majority of the interactions during the starter period were observed for FF and FQ, GS also influenced performance metrics when coupled with FF or FQ. Day 7 ending BW was influenced by interactions of GS and FQ. Broilers of the HY strain demonstrated greater d 7 BW when provided High FQ, whereas broilers of the FG strain demonstrated reductions in d 7 BW when given High FQ (P=0.046, Table 4.7). In a similar manner, d 0-10 FCR was also influenced by GS and FQ with a similar response of the lowest FCR being associated with HY broilers given High FQ, whereas FG broilers demonstrated the highest FCR when consuming High FQ; other treatment combinations performed intermediate(P=0.046, Table 4.7). Interactions between GS and FF for d 18 ending BW and d 0-18 BW gain (P=0.01, Table 4.8) demonstrated that broilers of the FG strain resulted similar performance, regardless of FF presented. However, broilers of the HY strain demonstrated higher d 18 BW and d 0-18 BW gain when presented crumbles in comparison to pellets.

The aforementioned interactions establish that relationships between the main effects of GS, FF, and FQ are complex. In general, it appears that greatest potential for interactions is associated with FF and FQ. Moreover, the resulting influence of these interactions is highly dependent on the performance metric, with significance being more readily established for ending BW and BW gain. However, GS influenced resulting d 18 BW and d 0-18 BW gain, in addition to d 0-10 FCR and d 7 ending BW, and should therefore be considered in future research considering the impacts of FF and FQ on starter performance. Therefore, the length of the starter period could heavily influence an

integrator's decision on which FF and FQ to employ, as results varied dependent on the day range.

Carryover performance (d 18-62)

As previously mentioned, common diets were manufactured at the same commercial integrator's mill and fed without further modification following the starter period to determine carryover performance. These common diets were fed in three phases including: grower (d 18-32), finisher (d 32-46) and withdrawal (d 46-62). Similar to the procedures conducted for obtaining descriptive data in the starter phase, representative samples were collected to determine descriptive data for percent pellets and surviving pellets [32]. Resulting values for each phase were: grower (76.6% Pellets, 75.3% surviving pellets), finisher (64.1% pellets, 64.5% surviving pellets) and withdrawal (80.1% Pellets, 69.1% surviving pellets). Resulting carryover performance (d 18-62) due to FF and FQ presented in the starter phase (d 0-18) can be located in Table 4.9.

Carryover effects due to starter FF and FQ presented from d 0-18 were not apparent for ending BW, BW gain, FI, average mortality, or CV of ending BW in the subsequent growth phases (i.e. d 0-32, 0-46, 0-62; P>0.05,Table 4.9). However, significant interactions were apparent for FCR at d 0-32 (FF x FQ) and d 0-46 (GS x FF x FQ). At d 0-32, broilers receiving 3388 µm from d 0-18 resulted in the lowest FCR as compared to broilers receiving 3008 µm or 80% IP which demonstrated the highest FCR; with other treatment combinations performing intermediate (P=0.031, Table 4.9). Although not significant, GS x FQ tended to influence d 0-32 FCR with broilers of HY

strain resulting in reductions in FCR as FQ improved with an opposite effect demonstrated for those of the FG strain (P=0.082, Table 4.9).

A three-way interaction between GS x FF x FQ was present for d 0-46 FCR (P=0.037, Figure 4.1). For HY strains, feeding pellets of 60% IP resulted in the lowest FCR as compared to 80% IP, with 40% IP preforming intermediate; crumbled treatments performed similar, regardless of FQ. However, FG strains performed statistically similar to one another regardless of FF x FQ combination, with the lowest numerical FCR being associated with broilers fed 2210 µm or 80% IP from d 0-18. These results suggest that HY broilers are more sensitive to changes in FQ and FF as compared to FG broilers. These findings are in agreement with Sellers and cohorts who demonstrated interactions for d 43 total pectoralis yield between GS x FF, with HY being more sensitive to FF; however, significant GS x FF interactions were not observed for performance [11]. Moreover, Lemons and cohorts demonstrated an interaction for d 46 ending BW between FF presented in the starter and finisher growth phase utilizing a HY strain [26]. Although the current study demonstrated improvements for feeding pellets in the starter phase, rather than crumbles, data from the current study and previous research suggests the potential for FF interactions occurring around 46 d of age [26].

Significance was not observed for any performance metric when examined for the entirety of the performance trial (d 0-62, Table 4.9). While only a trend, percent mortality appeared to be influenced by interactions between GS x FF and GS x FQ. For GS x FF, feeding pellets from d 0-18 to the HY strain increased mortality by approximately 5% as compared to crumbles, while feeding crumbles increased mortality by 2% for the FG strain compared to those receiving pellets (P=0.084, Table 4.9). In regards to GS x FQ,

broilers of a HY strain resulted in reduced mortality as FQ improved, with FG strains demonstrating a reduction in mortality when receiving Low FQ as compared to those receiving Medium or High FQ (P=0.052, Table 4.9). Mortality was high throughout the experiment, likely due to absence of antibiotics and anticoccidials in the diets, as this commercial integrator implements no-antibiotic ever (NAE) programs. Mortalities were posted and cause of death was recorded. Necrotic enteritis was found to be major cause of mortality, likely due to coccidiosis vaccination occurring at the hatchery and implementation of used litter. Litter sampling at the conclusion of the trial confirmed the presence of *Clostridium perfringens* (data not presented).

Performance Discussion

During the starter period, interactions were most apparent between FF x FQ. More specifically, BW and BW gain were more commonly impacted as compared to FCR. Previous research examining the effects of starter FF have primarily focused on crumble particle size impacts on starter performance [10, 24, 26, 52]. In many of these cases, FCR improvements due to crumble particle size have been more commonly established in comparison to BW gain, making the findings of the current study intriguing. However, as previously mentioned, the majority of these studies only employed crumbles, with average particle sizes much smaller than currently implemented in the current study (< 2000 µm). Furthermore, few studies have explored the potential to feed pelleted diets during the starter period to improve performance.

Serrano and cohorts explored the potential to provide pelleted diets during the starter phase (d 1-21) to elucidate performance differences in comparison to crumbled

and mash diets [53]. Utilizing two performance periods (d 1-11 and d 11-21), average daily gain and FCR was improved for Ross 308 male broilers when provided crumbled or pelleted diets as compared to mash diets. However, examining the entire starter period (d 1-21), associated FCR improvements due to pellets were 0.09 and 0.35 in comparison to broilers receiving crumbles and mash, respectively. Although these results suggest that pellets may be fed to improve starter performance, particularly to benefit FCR, descriptive data detailing average particle size or intact pellet percentages was not presented, making comparisons with the current study difficult.

Cerrate and cohorts examined the potential to feed micropellets (1.59 and 3.17 mm diameter) during the starter phase to improve Cobb 500 starter (d 0-13) performance) [25]. Micropellets resulted in associated FCR improvements in comparison to broilers fed unconditioned mash, with crumbled treatments performing similar to micropellets. However, separation between micropellets and crumbles was not apparent. Similar to the Serrano experiment, descriptive data was not presented making comparisons difficult. Also, it is important to note that this previous research has primarily focused on differences in FF, without considering differences in FQ of similar FF. It may be argued that experiments examining differences in crumble particle size inherently compare differences in feed quality as these factors may be nested. However, the majority of these experiments often compare only two differing crumble particle sizes, making meaningful comparisons to the current study difficult [10, 26, 52].

Two recent experiments in our laboratory compared the impact of feeding five or eight different crumble particle sizes of common diets on starter performance (d 0-14). The first experiment utilized five crumble particle sizes ranging from 1202 to 2172 µm.

Results from this experiment demonstrated a 0.03 improvement in FCR associated with crumbles of 1760 or 2172 µm; without apparent differences in d 14 ending BW and BW gain [24]. The second experiment utilized eight crumble particle sizes ranging from 1174 to 3736 µm. As demonstrated in experiment 1, similar improvements in FCR were apparent as crumble particle size increased. Conversely, BW and BW gain was generally improved by approximately 30 g for broilers receiving diets 2800 µm or greater. The results from the current experiment are in agreement with experiment 2, as the current trial employed crumble particle sizes of 2210 µm or greater. Moreover, the reduction in d 18 BW associated with 40% IP (average particle size of 1732 µm, Table 4.3) in the current trial demonstrated a similar response to a crumble particle size tested in experiment 2 (1883 µm).

The authors believe the lack of separation between the crumbled treatments for d 0-18 BW gain to be associated with the implementation of particle sizes large enough to not result in detrimental performance [24]. In particular, Lemons and cohorts demonstrated improvements associated with d 0-14 BW gain for feeding crumbles greater than 2800 µm; with crumbles of 2257 µm performing similar, which was close to the Low crumbles implemented in the current study (i.e. 2210 µm) [24]. It is interesting to note that there are not associated improvements for FCR in the current study, as previous works demonstrated linear relationships of improved FCR via increased crumble particle size [24]. Perhaps this lack in FCR benefit in the current study may be partially explained by deviations of each FQ for both FF.

In an effort to help explain the lack of separation for associated BW gain benefits, resulting particle retention (based on corresponding sieves used for average particle size

analysis) was plotted for each FQ; Low (Figure 4.2), Medium (Figure 4.3), and High (Figure 4.4). These figures give a nice visual representation that the FF of crumbles resulted in an even distribution of ranging particle sizes, whereas the FF of pellets were bimodal in nature. Therefore, the improvements associated with the FF of crumbles from d 0-10 and d 0-14 BW gain may be attributed to the nature of birds being able to select the desired particle based on bird beak capacity. However, it is interesting to note that birds receiving 80% IP were able to overcome the deficit in particle size distributions. Perhaps this may due to large particle sizes allowing for similar BW at these periods as compared to those receiving 40 or 60% IP. One may argue that High FQ for both FF are the same treatment due to similarities in average particle size (i.e. 3388 vs 3411 μm) which may confound results. However, looking at particle size distribution (Figure 4. 4), the authors believe that these treatments are in fact different and warrants the investigation of better assays for obtaining descriptive data for pelleted treatments due to their bimodal nature and uneven distribution.

Although performance differences were apparent during the starter phase in the current study, carryover effects were limited, with improvements only being demonstrated for FCR. Previous work examining the potential for carryover effects due to FF presented during the starter growth phase (d 0-13) failed to demonstrate benefits at d 34 and 41 for BW and FCR after common diets were presented [25]. While the current study did not translate to improvements in BW, improvements in FCR observed in the current study (i.e. d 0-32 and d 0-46) were similar to the date ranges of the aforementioned study that failed to demonstrate carryover effects [25]. A three-way interaction for d 0-46 FCR in the current study was particularly interesting due to this

being the only three way interaction observed in the performance trial. Although the majority of interactions observed were between FF x FQ, this interaction illustrates the complexity and importance between all three factors (i.e. GS, FF, and FQ) explored in the current trial. One important aspect warranting consideration is the current study did not explore the potential for interactive effects of FF and FQ in subsequent phases. Due to the potential for FF to interact between dietary phases [26, 53, 54], it is quite possible that broiler performance could be further improved if different FF were presented in subsequent growth phases following FF and FQ presented in the starter phase.

Processing

Resulting tissue weights and wooden breast severity (WBS) are located in Table 4.10. Tissue weights were converted to yields relative to d 62 live BW (YBW) and d 63 carcass weight YCW; Table 4.11). Abdominal fat pad weight was the only processing metric demonstrating a significant interaction for tissue weights (GS x FQ, P=0.023, Table 4.10). Broilers of the FG strain demonstrated increased weight for abdominal fat pads, with HY broilers receiving Low FQ resulting in a similar fat pad weight in comparison to FG broilers fed Low or High FQ. Furthermore, HY broilers receiving Medium FQ had the lowest fat pad weight with FG broilers demonstrating the highest fat pad weight when fed Medium FQ. This translated into similar effects when placed on a yield relative to BW and CW (P=0.035, P=0.027, Table 4.11, respectively).

While not significant for tissue weight, pectoralis major yield for both BW and CW demonstrated significant three-way interactions (GS x FF x FQ; P=0.035, Figure 4.5; P=0.037, Figure 4.6, respectively). High yielding broilers demonstrated the greatest

pectoralis YBW when provided 2210 µm or 80% IP, with birds fed 40% IP resulting in the lowest YBW; other treatment combinations performed intermediate (P=0.035, Figure 4.5). Broilers of the FG strain resulted in the greatest YBW when provided 40% IP as compared to broilers receiving 3008 or 3388 µm, which resulted in the lowest YBW; other combinations performed intermediate. Similar responses were observed when placed on YCW with a few minor differences in the separation of treatment means. Broilers of the HY strain once again demonstrated the highest YCW when provided 2210 µm or 80% IP. However, feeding 40 or 60% IP resulted in the lowest YCW (P=0.037, Figure 4.6). Fast growing broilers resulted in the highest YCW when fed 40% IP in comparison to 3008 µm, with other combinations performing intermediate. These findings are in agreeance with Sellers and cohorts who demonstrated improved 43 pectoralis major yields for HY broilers when fed 80% IP [11]. Moreover, FG broilers had similar d 43 pectoralis major yields, regardless of IP (i.e. 50, 60, 70 or 80%) presented. While processing dates differed between studies, these data suggest that HY broilers are more sensitive to increasing FF as compared to those of a FG strain; particularly for the metric of breast yield.

The main effect of FQ affected WBS and wing weights and yields. For WBS, providing Low FQ resulted in higher incidences of wooden breast as compared to those receiving Medium or High FQ. This finding was interesting as WBS is a relatively new phenomenon facing our industry, and the impacts of FF and FQ on WBS have not been explored to our knowledge. It has been suggested that WBS incidence is associated with broilers exhibiting a high growth rate [44]. Due to increases in FQ typically resulting in improved performance (i.e. growth rate), one may speculate that increased FQ would

increase the incidence of WBS; making the current findings somewhat counter-intuitive. However, it should be mentioned that while significant differences existed, the scale for wooden breast severity is placed on whole integers (e.g. 0-3) and the resulting values for all FQ in the current trial would be an average value of 1, making the implications on processing condemnations due to WBS difficult. Therefore, future research examining the effects of FQ on WBS are warranted.

Feeding broilers Low FQ resulted in a 12 g improvement in wing weight compared to those receiving High FQ, with Medium FQ performing intermediate (P=0.019, Table 4.10). However, wing YCW and YBW resulted in differing separation dependent on the metric used. Feeding broilers Low or Medium FQ resulted in higher YBW as compared those receiving High FQ (P=0.015, Table 4.11). For wing YCW, feeding Medium FQ resulted in an improved yield compared to those receiving Low or High FQ (P=0.012, Table 4.11). Due to three-way interactions between GS x FF x FQ, integrators may want to present different FF and FQ during the starter phase dependent on the GS they are utilizing. These data suggest that integrators should provide 2210 μm crumbles, or 40 or 80% IP from d 0-18 for improvements in pectoralis major yields. However, integrators of the FG strain should remain cognizant of providing 40% IP to improve pectoralis major yields as Low FQ resulted in higher WBS.

Summary

The current study demonstrated FF and FQ presented in the starter phase had the most pronounced effects on BW and BW gain, with associated carryover effects/improvements dependent upon the specific date range. However, the current study

suggests that FQ may be more important if feeding pellets from d 0-18 in comparison to crumbles, due to similarities in crumbled treatments. Interactions were not apparent during the starter period for d 0-18 FCR. However, trends for d 0-18 FCR demonstrated similar responses as demonstrated for d 18 ending BW and 0-18 BW gain, likely influenced by FQ, which established reductions in d 0-18 FCR as FQ improved. Gastrointestinal measurements were influenced by the main effects of FF and FQ; with the primary impact on small intestine lengths, yields, and illeum pH. Although clear connections to observed performance were not established, correlation data suggested that BW and BW gain demonstrate negative relationships with small intestine yields at early stages in the broiler's lifecycle.

Carryover effects due to starter FF and FQ were not readily apparent. FCR was influenced at d 32 and 46, suggesting that the role of FF and FQ is particularly complex and may be influenced by GS at certain age ranges (i.e. d 46). The intended target market may influence an integrator's decision for which FF and FQ to present during the starter growth phase. Depending upon GS utilized, these data suggest different goals in FQ should be targeted; particularly for HY broilers as the current data suggests more sensitivity to changes in FF. Based on the results from the current trial, integrators in the "fast-food" market may benefit from feeding 3388 µm crumbles due to improvements in d 0-32 FCR. For integrators targeting the "small" tray-pack market or "roasters", the decision becomes increasingly complex as GS influences associated improvements/detriments when coupled with FF and FQ. The current study suggests feeding 60% IP for HY strains, whereas 2210 µm crumbles or 80 % IP should be presented to broilers of FG strains. Integrators in the traditional tray pack markets may be

less concerned with FF and FQ presented in the starter due to absence of carryover effects in overall performance (d 0-62). However, FF and FQ may still warrant consideration for integrators rearing heavy broilers due to differences in pectoralis major yields although improvements in performance were not demonstrated.

It is important to note that the impacts due to starter FF and FQ observed in the current study may be differ based upon FQ presented in subsequent growth phases; due to the potential for starter FF to interact as demonstrated in previous research [26,54]. Overall, it appears that the length of the desired grow out necessitates which FF and FQ to present during the starter growth phase.

Conclusions and Applications

1. Feed form and FQ interacted to influence d 18 ending BW and d 0-18 BW gain. These data demonstrated similar performance among birds fed crumbled treatments (regardless of FQ), whereas increasing FQ in pelleted treatments improved d 18 ending BW and 0-18 BW gain.

2. Improvements in FQ resulted in a 0.015 improvement in d 0-18 FCR, whereas feeding crumbles (regardless of FQ) resulted in an 0.011 improvement in d 0-18 FCR.

3. Carryover effects due to FF and FQ presented in the starter growth phase influenced d 0-32 and d 0-46 FCR, demonstrating that the roles of FF and FQ are complex. Therefore, FF/FQ presented during the starter growth phase may vary depending the length of the grow-out, desired market, and GS implemented.

4. Pectoralis major yields were influenced by GS, FF, and FQ, suggesting that broilers of HY strains should be provided 2210 µm or 80% IP from d 0-18 may improve pectoralis major yields; whereas, FG broilers should be provided 40% IP from d 0-18.

5. Gastrointestinal development was influenced by the main effects of FF and FQ. In general, the majority of effects where demonstrated during the early stages of the starter growth phase. In particular, providing the FF of pellets (regardless of FQ) reduced small intestine length (differing sections), whereas high FQ (regardless of FF) reduced relative organ weight. However, consistent effects in relation to observed performance were unclear, warranting further research.

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Table 4.1 Treatment outline for experimental diets differing in feed form and feed quality presented to two different genetic strains during the starter growth phase (d 0-18)[1].

Treatment	Genetic Strain	Feed Form	Feed Quality
1	High-Yielding	Crumbles	Low- 2210 µm
2			Medium- 3008 µm
3			High- 3388 µm
4		Pellets	Low- 40% IP
5			Medium-60% IP
6			High-80% IP
7	Fast-Growing	Crumbles	Low- 2210 µm
8			Medium- 3008 µm
9			High- 3388 µm
10		Pellets	Low- 40% IP
11			Medium-60% IP
12			High-80% IP

[1]Following the starter growth phase, common diets without further modification were fed to all treatments to determine the potential carryover effect due to feed form and feed quality presented in the starter growth phase.

Table 4.2 Analyzed nutrients for feed presented in each dietary growth phase to straight-run broilers of two genetics strains[1].

Analyzed Nutrient	Starter (d 0-18)	Grower (d 18-32)	Finisher (d 32-46)	Withdrawal (d46 -62)
Gross Energy[2] (kcal/kg)	3494	3315	3138	2994
Crude Protein[3] (%)	21.76	20.80	20.25	19.49
Crude Fat [4] (%)	3.88	4.18	4.00	4.22
Total Calcium[5] (%)	0.68	0.71	0.55	0.72
Total Phosphorus[6] (%)	0.58	0.51	0.50	0.52

[1]Values are means of duplicate samples obtained from ATC Scientific (North Little Rock, AR)
[2]Determined using bomb calorimetry.
[3]Determined using "Protein (Crude) in Animal Feed, Combustion Method" (AOAC 990.03).
[4]Determined using "Fat (Crude) or Ether Extract in Pet Food"(AOAC 954.02).
[5]Determined using "Metal and Other Elements in Plants and Pet Foods. Inductively Coupled Plasma (ICP) Spectroscopic Method (AOAC 985.01).
[6]Determined using "Metal and Other Elements in Plants and Pet Foods. Inductively Coupled Plasma (ICP) Spectroscopic Method (AOAC 985.01)

Table 4.3 Descriptive feed manufacture data for experimental diets fed during the starter growth (d 0-18) phase[1].

Feed Form	Feed Quality	Average Particle Size[2] (µm)	Standard Deviation (±)	Average NHPT[3,4] (%)	Production Rate[5] (tonne/ h)
Crumbles	Low	2210	2.50	92.70	41.10
	Medium	3008	2.05		
	High	3388	1.88		
Pellets	Low	1732	3.03		
	Medium	2112	2.85		
	High	3411	2.08		

[1]All diets were conditioned at 88°C and extruded through a 4.37 mm diameter pellet die with an effective length of 25 mm.
[2]Particle Size determined using RO-TAP RX-29 for 10 minutes (ASAE 1997b); performed in duplicate.
[3]New Holman Pellet Tester; performed for 30 s processing period using ASAE 1997a; performed in duplicate.
[4]Pellets were sifted through No. 5 American Society of Agricultural Engineers (ASAE) screen and 100 g of sifted pellets were placed in holding chamber, blown for 30 s by a jet of air, then weighed, giving a direct read of pellet survivability. Fines are removed during the blowing process.
[5]Determined using automated reading from commercial integrator's automated pelleting program.

Table 4.4 Comparisons for the main effects of FF and FQ on d 3, 5, and 7 gastrointestinal development during the starter period (d 0-18)[1].

FF[2]	FQ[3]	Length (cm)			pH[4]		Weight (g)		Relative Organ Weight[5,6] (%)					
		Duodenum	Jejunum	Ileum	Gizzard	Ileum[7]	Crop Fill[8]	Yolk Sack	Gizzard	Proventriculus	Pancreas	Duodenum	Jejunum	Ileum
Day 3														
C	-	13.573	29.702	27.556[a]	2.604	6.678	0.644	0.489	4.940	1.135	0.414	1.256	1.827[b]	1.533
P	-	13.587	28.980	26.471[b]	2.517	6.626	0.651	0.504	5.031	1.141	0.395	1.296	1.928[a]	1.533
Probability Value		0.657	0.277	0.024	0.451	0.714	0.931	0.813	0.534	0.609	0.332	0.113	0.009	0.703
SEM		0.135	0.427	0.368	0.053	0.056	0.054	0.029	0.051	0.017	0.013	0.022	0.030	0.029
-	Low[9]	13.783	29.417	26.995	2.596	6.595[b]	0.585	0.484	4.900	1.112	0.408	1.327[a]	1.955[a]	1.556
-	Med.[10,11]	13.358	29.225	26.789	2.535	6.776[a]	0.690	0.490	4.998	1.163	0.375	1.304[a]	1.895[a]	1.544
-	High[12]	13.600	29.381	27.256	2.551	6.585[b]	0.668	0.515	5.058	1.140	0.430	1.197[b]	1.782[b]	1.499
Probability Value		0.160	0.858	0.703	0.901	0.019	0.491	0.890	0.280	0.273	0.068	0.003	0.001	0.115
SEM		0.166	0.523	0.450	0.065	0.069	0.066	0.035	0.063	0.021	0.016	0.027	0.036	0.035
Day 5														
C	-	14.504	32.888	32.076	2.430[a]	6.038[a]	0.586	0.216	4.291	1.079	0.473	1.362	2.117	1.623
P	-	14.329	32.727	31.593	2.277[b]	5.768[b]	0.608	0.203	4.409	1.096	0.478	1.402	2.191	1.670
Probability Value		0.512	0.836	0.828	0.005	0.032	0.815	0.945	0.115	0.864	0.603	0.536	0.324	0.602
SEM		0.173	0.463	0.472	0.038	0.089	0.065	0.018	0.046	0.017	0.012	0.027	0.039	0.033
-	Low	14.629	32.970	32.376	2.354	5.693[b]	0.564	0.215	4.361	1.096	0.480	1.459	2.260[a]	1.740[a]
-	Med.	14.391	32.757	31.598	2.273	6.038[a]	0.587	0.204	4.393	1.049	0.474	1.338	2.104[b]	1.629[ab]
-	High	14.231	32.694	31.528	2.434	5.978[ab]	0.639	0.209	4.296	1.118	0.473	1.349	2.099[b]	1.571[b]
Probability Value		0.101	0.619	0.419	0.084	0.037	0.794	0.837	0.710	0.114	1.000	0.075	0.036	0.042
SEM		0.212	0.567	0.578	0.047	0.109	0.080	0.023	0.056	0.020	0.015	0.033	0.048	0.041
Day 7														
C	-	16.481	39.281[a]	36.594	2.565	6.156	0.759	0.096	3.823	0.899	0.476	1.446	2.362	1.778
P	-	16.616	38.130[b]	35.807	2.420	6.208	0.886	0.110	3.858	0.894	0.483	1.475	2.383	1.765
Probability Value		0.750	0.030	0.372	0.137	0.128	0.280	0.591	0.623	0.971	0.924	0.262	0.704	0.810
SEM		0.241	0.439	0.375	0.064	0.074	0.082	0.017	0.053	0.014	0.011	0.036	0.041	0.036
-	Low	16.551	38.880	36.404	2.450	6.233[a]	0.748	0.092	3.900	0.907	0.477	1.450	2.394	1.773
-	Med.	16.969	39.450	36.738	2.514	5.952[b]	0.747	0.111	3.798	0.891	0.474	1.482	2.417	1.805
-	High	16.125	37.785	35.459	2.514	6.361[a]	0.973	0.106	3.823	0.890	0.487	1.449	1.306	1.737
Probability Value		0.190	0.178	0.084	0.841	0.009	0.195	0.773	0.352	0.489	0.728	0.640	0.260	0.702
SEM		0.294	0.539	0.460	0.079	0.090	0.100	0.021	0.065	0.017	0.013	0.044	0.051	0.045

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$)

[1]One bird per pen was randomly chosen for each sampling period (d 10, 14, or 18) to determine gastrointestinal measurements.

[2]FF= Feed Form; C=Crumbles; P=Pellets.

[3]FQ=Feed Quality; Low and High treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of Low:High Crumbles being hand mixed for creation of the Medium Treatment; Low, Medium, and High treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% IP, respectively.

[4]pH measured before removal of digesta.

[5]Digesta was emptied prior to recording of organ weight.

[6] Individual bird weights were taken before euthanasia to allow for determination of relative organ weight using the following equation: (Organ Weight/ BW) x 100).

[7]Ileum pH was recorded at terminal ileum prior to the ileal-cecal junction.

[8]Mositure was removed from crop fill contents using a drying oven at 105°C for 16 h prior to analysis.

[9]Birds receiving Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.

[10]Med.=Medium FQ.

[11]Birds receiving Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.

[12]Birds receiving High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.

Table 4.5 Comparisons for the main effects of FF and FQ on d 10, 14, and 18 gastrointestinal development during the starter period (d 0-18)[1].

FF[2]	FQ[3]	Length (cm)			pH[4]		Weight (g)		Relative Organ Weight[5,6]					
		Duodenum	Jejunum	Ileum	Gizzard	Ileum[7]	Crop Fill[8]	Yolk Sack	Gizzard	Proventriculus	Pancreas	Duodenum	Jejunum	Ileum
Day 10														
C	-	18.247	42.715	39.004	2.403	6.439	0.659	0.055	3.242	0.769	0.488	1.406	2.242	1.595
P	-	18.426	41.194	38.949	0.392	6.481	0.521	0.052	3.397	0.775	0.507	1.480	2.262	1.625
Probability Value		0.284	0.108	0.863	0.741	0.635	0.225	0.782	0.213	0.418	0.303	0.098	0.729	0.392
SEM		0.155	0.471	0.502	0.044	0.050	0.080	0.010	0.047	0.010	0.010	0.021	0.034	0.026
-	Low[9]	18.521[a]	42.167	39.313	2.352	6.422	0.516	0.057[ab]	3.443	0.794	0.502	1.432	2.243	1.678[a]
-	Med.[10,11]	18.333[ab]	42.020	38.931	2.382	6.513	0.711	0.027[b]	3.275	0.757	0.511	1.478	2.277	1.597[ab]
-	High[12]	18.155[b]	41.678	38.687	2.457	6.446	0.544	0.078[a]	3.240	0.764	0.480	1.420	2.236	1.556[b]
Probability Value		0.032	0.553	0.557	0.714	0.736	0.314	0.004	0.306	0.071	0.090	0.411	0.813	0.029
SEM		0.190	0.577	0.614	0.054	0.061	0.098	0.012	0.057	0.012	0.012	0.026	0.042	0.032
Day 14														
C	-	21.016	50.770	48.243	2.656	5.917	1.396	0.045	2.773	0.642	0.402	1.211	2.000	1.329
P	-	20.847	49.524	48.615	2.521	5.859	1.373	0.029	2.828	0.630	0.402	1.189	1.989	1.313
Probability Value		0.886	0.172	0.358	0.078	0.420	0.926	0.356	0.176	0.469	0.583	0.639	0.566	0.679
SEM		0.244	0.573	0.625	0.050	0.086	0.175	0.010	0.036	0.009	0.007	0.021	0.035	0.027
-	Low	21.447	50.050	48.188	2.516[b]	5.891	1.576	0.050	2.780	0.646	0.406	1.195	2.001	1.303
-	Med.	20.377	49.959	48.084	2.505[b]	5.972	1.123	0.019	2.796	0.624	0.394	1.192	2.027	1.301
-	High	20.969	50.432	49.016	2.744[a]	5.801	1.454	0.041	2.826	0.637	0.405	1.212	1.956	1.359
Probability Value		0.270	0.790	0.590	0.014	0.630	0.317	0.510	0.514	0.801	0.906	0.802	0.614	0.329
SEM		0.299	0.704	0.766	0.061	0.105	0.214	0.013	0.045	0.010	0.009	0.025	0.043	0.033
Day 18														
C	-	23.050	56.509	54.341[b]	2.794	6.263	1.384	0.023	2.482	0.548	0.379	1.062	1.931	1.395
P	-	22.939	56.924	56.196[a]	2.629	6.245	1.245	0.011	2.433	0.537	0.380	1.013	1.828	1.363
Probability Value		0.866	0.685	0.047	0.120	0.630	0.552	0.059	0.485	0.198	0.692	0.288	0.065	0.762
SEM		0.279	0.702	0.648	0.064	0.085	0.163	0.005	0.038	0.010	0.007	0.023	0.040	0.028
-	Low	22.777	56.092	54.100[b]	2.627	6.295	0.937[b]	0.019	2.578[a]	0.554	0.389	1.055	1.914	1.378
-	Med.	23.397	56.429	54.389[b]	2.758	6.313	1.129[b]	0.012	2.356[b]	0.534	0.375	1.038	1.848	1.377
-	High	22.808	57.628	57.316[a]	2.750	6.153	1.878[a]	0.018	2.438[b]	0.540	0.374	1.019	1.877	1.383
Probability Value		0.507	0.178	0.004	0.608	0.662	0.003	0.794	0.018	0.637	0.458	0.698	0.806	0.681
SEM		0.342	0.860	0.793	0.079	0.104	0.200	0.006	0.047	0.012	0.009	0.028	0.049	0.035

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$)

[1]One bird per pen was randomly chosen for each sampling period (d 10, 14, or 18) to determine gastrointestinal measurements.

[2]FF= Feed Form; C=Crumbles; P=Pellets.

[3]FQ=Feed Quality; Low and High treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of Low:High Crumbles being hand mixed for creation of the Medium Treatment; Low, Medium, and High treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% IP, respectively.

[4]pH measured before removal of digesta.

[5]Digesta was emptied prior to recording of organ weight.

[6] Individual bird weights were taken before euthanasia to allow for determination of relative organ weight using the following equation: (Organ Weight/ BW) x 100).

[7]Ileum pH was recorded at terminal ileum prior to the ileal-cecal junction.

[8]Mositure was removed from crop fill contents using a drying oven at 105°C for 16 h prior to analysis.

[9]Birds receiving Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.

[10]Med.=Medium FQ.

[11]Birds receiving Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.

[12]Birds receiving High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.

Table 4.6 Correlation to examine relationships of significant gastrointestinal measurements (d 3, 5, 7, 10, 14, and 18) interactions relative to BW, BW gain, feed intake, and FCR for two GS fed diets differing in FF and FQ during the starter period (d 0-18)[1,2].

Gastrointestinal Measurement	Day	Significant Interaction[3,4]	Ending BW		BW Gain		Feed Intake/bird[5]		FCR[6]	
			r	P-Value	r	P-Value	r	P-Value	r	P-Value
Duodenum Length	18	GS x FF x FQ	-	0.841	-	0.870	-	0.445	-	0.330
Jejunum Length	14	GS x FF	-	0.943	-	0.951	-	0.914	-	0.828
Ileum Length	10	FF x FQ	-	0.541	-	0.360	-	0.633	-	0.384
	14	FF x FQ	-	0.079	-	0.065	-	0.172	-	0.893
Ileum pH[7]	5	GS x FF	0.343	0.001	0.329	0.001	-	-	-	-
	10	GS x FF	-	0.129	-	0.157	0.230	0.019	-	0.653
Yolk Sack Weight	10	GS x FQ	-	0.368	-	0.420	-	0.908	-	0.382
Crop Fill[8]	18	GS x FF x FQ	-	0.059	-	0.063	-	0.816	-0.208	0.038
Relative Gizzard Weight[9]	7	FF x FQ	-0.272	0.005	-.263	0.007	-	0.304	-	0.446
	10	GS x FF	-	0.053	-	0.068	-	0.197	0.222	0.025
	14	GS x FF x FQ	-	0.788	-	0.912	-	0.814	-	0.875
Relative Proventriculus Weight[10]	10	GS x FF x FQ	-	0.681	-	0.506	-	0.406	-	0.821
Relative Duodenum Weight[11]	3	FF x FQ	-	0.922	-	0.985	-	-	-	-
	7	FF x FQ	-0.420	<0.001	-0.424	<0.001	-	0.550	0.323	0.001
Relative Jejunum Weight[12]	5	GS x FQ	-0.246	0.012	-0.263	0.007	-	-	-	-
Relative Ileum Weight[13]	18	FF x FQ	-	0.402	-	0.377	-	0.107	-	0.295

[1]One bird per pen was randomly chosen for each sampling period (d 10, 14, or 18) to determine gastrointestinal measurements.
[2]Correlation analyses utilized gastrointestinal measurements from the randomly selected bird in relationship to the pen's average ending BW, BW gain, feed intake/bird, and FCR for the respective day.
[3]Signficiant interaction (P≤0.05) between the main effects of Genetic Strain (GS), Feed Form (FF), and/or Feed Quality (FQ) that warranted correlation analyses.
[4]Two genetic strains (High Yielding or Fast Growing) were presented one of two FF (Crumbles or Pellets) at one of three qualities (Low, Medium, or High) during the starter period (d 0-18).
[5]Correlation analysis for feed intake/bird could not be performed on d 3 and 7.
[6]Correlation analysis for FCR could not be performed on d 3 and 7.
[7]Ileum pH was recorded at terminal ileum prior to the ileal-cecal junction prior to removal of digesta.
[8]Mositure was removed from crop fill contents using a drying oven at 105°C for 16 h prior to analysis.
[9]Relative Gizzard Weight: (Gizzard weight (digesta removed)/Individual BW x 100).
[10]Relative Proventriculus Weight: (Proventriculus weight (digesta removed)/Individual BW x 100).
[11]Relative Duodenum Weight: (Duodenum weight (digesta removed)/Individual BW *100).
[12]Relative Jejunum Weight: (Jejunum weight (digesta removed)/Individual BW *100).
[13]Relative Ileum Weight: (Ileum weight (digesta removed)/Individual BW *100).

Table 4.7 Comparisons of straight-run broiler performance for two GS[1] fed diets differing in FF[2] and FQ[3] during the starter period (d 0-18) at specific date ranges.

GS[1]	FF[2]	FQ[3]	Chick Weight (kg)	Ending BW (kg)			BW Gain (kg)			Feed Intake/bird (kg)			Mortality (%)			FCR			CV of Ending BW (%)		
Day/Date Range			0	7	10	14	0-7	0-10	0-14	0-7	0-10	0-14	0-7	0-10	0-14	0-7	0-10	0-14	7	10	14
Main Effects-Feed Form																					
-	C	-	0.041	0.171^{a}	0.271^{a}	0.457^{a}	0.130^{a}	0.230^{a}	0.416^{a}	0.151^{b}	0.297^{b}	0.547	1.404	2.284	3.373	1.121^{b}	1.224^{b}	1.234^{b}	11.095	11.586	12.010
-	P	-	0.041	0.163^{b}	0.260^{b}	0.446^{b}	0.122^{b}	0.220^{b}	0.406^{b}	0.155^{a}	0.303^{a}	0.542	2.164	2.983	3.964	1.213^{a}	1.301^{a}	1.253^{a}	11.746	11.841	11.461
SEM			9.58*10^{-5}	0.001	0.001	0.003	0.001	0.001	0.003	0.001	0.002	0.003	0.424	0.526	0.642	0.010	0.009	0.004	0.331	0.442	0.385
Main Effects-Feed Quality																					
-	-	Low[4]	0.041	0.166	0.263	0.446	0.125	0.222	0.405	0.152	0.298	0.543	1.97	2.742	3.772	1.167	1.262	1.253^{a}	11.152	11.640	11.750
-	-	Med.[5,6]	0.041	0.169	0.268	0.453	0.128	0.227	0.412	0.154	0.302	0.547	1.527	2.495	3.567	1.164	1.260	1.241^{ab}	11.295	11.777	11.653
		High[7]	0.041	0.167	0.266	0.457	0.126	0.225	0.415	0.153	0.300	0.543	1.852	2.663	3.668	1.169	1.266	1.237^{b}	11.816	11.724	11.803
SEM			1.17*10^{-4}	0.001	0.002	0.003	0.001	0.002	0.003	0.001	0.002	0.004	0.519	0.644	0.787	0.012	0.010	0.005	0.405	0.542	0.472
Genetic Strain x Feed Form Interactions																					
HY	C	-	0.042	0.174	0.273	0.452	0.132	0.231	0.410	0.153	0.297	0.543	0.772	1.618	2.028	1.116	1.214	1.236	11.297	11.059	12.094
	P	-	0.042	0.164	0.260	0.438	0.123	0.218	0.396	0.157	0.303	0.534	2.167	2.906	3.888	1.223	1.302	1.259	12.753	12.532	12.447
FG	C	-	0.040	0.168	0.268	0.463	0.128	0.228	0.423	0.149	0.297	0.550	2.036	2.951	4.719	1.126	1.235	1.232	10.893	12.113	11.925
	P	-	0.040	0.162	0.261	0.455	0.122	0.221	0.415	0.153	0.304	0.550	2.161	3.060	4.040	1.203	1.300	1.248	10.740	11.150	10.475
SEM			1.35 *10-4	0.001	0.002	0.004	0.001	0.002	0.004	0.001	0.003	0.004	0.600	0.743	0.908	0.014	0.012	0.005	0.468	0.625	0.544
Genetic Strain x Feed Quality Interactions																					
HY	-	Low	0.042	0.167^{abc}	0.263	0.438	0.125	0.221	0.396	0.155	0.301	0.538	2.093	3.151	3.800	1.190	1.278^{ab}	1.257	11.661	11.410	12.309
	-	Med.	0.042	0.169^{ab}	0.266	0.444	0.127	0.225	0.402	0.155	0.301	0.541	1.157	1.932	3.042	1.160	1.252^{ab}	1.248	12.260	12.262	12.164
	-	High	0.042	0.171^{a}	0.270	0.453	0.129	0.228	0.411	0.155	0.298	0.537	1.157	1.702	2.032	1.157	1.245^{b}	1.238	12.155	11.714	12.339
FG	-	Low	0.040	0.164^{bc}	0.263	0.454	0.125	0.223	0.414	0.149	0.295	0.547	1.852	2.334	3.744	1.144	1.247^{ab}	1.249	10.642	11.869	11.191
	-	Med.	0.041	0.168^{ab}	0.270	0.462	0.128	0.229	0.422	0.153	0.304	0.554	1.897	3.058	4.092	1.169	1.268^{ab}	1.235	10.330	11.292	11.142
	-	High	0.040	0.162^{c}	0.262	0.460	0.122	0.221	0.420	0.151	0.302	0.549	2.546	3.623	5.303	1.181	1.288^{a}	1.236	11.477	11.733	11.267
Feed Form x Feed Quality																					
-	C	2210µm	0.041	0.170	0.270^{ab}	0.456^{ab}	0.130	0.229^{ab}	0.415^{ab}	0.151	0.297	0.549^{abc}	1.389	2.092	3.239	1.112	1.216	1.237	11.280	11.948	11.703
-		3008µm	0.041	0.174	0.276^{a}	0.462^{a}	0.133	0.235^{a}	0.421^{a}	0.152	0.300	0.556^{a}	1.434	2.334	3.334	1.118	1.226	1.234	10.722	11.374	12.141
-		3388µm	0.041	0.168	0.267^{bc}	0.454^{ab}	0.127	0.226^{bc}	0.413^{ab}	0.149	0.293	0.535^{c}	1.389	2.427	3.547	1.133	1.232	1.231	11.284	11.436	12.185
-	P	40% IP[8]	0.041	0.161	0.256^{d}	0.436^{c}	0.120	0.215^{d}	0.395^{c}	0.153	0.298	0.537^{bc}	2.556	3.393	4.305	1.222	1.309	1.269	11.024	11.332	11.798
-		60% IP	0.041	0.163	0.260^{cd}	0.444^{bc}	0.123	0.220^{cd}	0.403^{bc}	0.156	0.304	0.539^{bc}	1.620	2.657	3.800	1.211	1.294	1.249	11.868	12.180	11.165
-		80% IP	0.041	0.165	0.264^{bc}	0.459^{a}	0.124	0.224^{bc}	0.418^{a}	0.157	0.307	0.551^{ab}	2.315	2.899	3.788	1.205	1.300	1.242	12.348	12.011	11.421
SEM			1.66*10-4	0.002	0.002	0.005	0.002	0.002	0.005	0.002	0.003	0.005	0.734	0.911	1.112	0.017	0.015	0.006	0.573	0.766	0.666
Main Effect and Interaction Probabilities																					
GS			<0.001	0.007	0.395	0.001	0.126	0.941	0.001	0.006	0.918	0.013	0.298	0.321	0.122	0.731	0.450	0.156	0.012	0.795	0.054
FF			0.277	<0.001	<0.001	0.005	<0.001	<0.001	0.006	0.002	0.022	0.342	0.209	0.351	0.518	<0.001	<0.001	0.001	0.169	0.686	0.320
FQ			0.313	0.244	0.131	0.083	0.240	0.117	0.086	0.357	0.447	0.643	0.823	0.963	0.984	0.963	0.912	0.042	0.480	0.984	0.975
GS x FF			0.586	0.347	0.109	0.448	0.329	0.101	0.0460	0.894	0.829	0.282	0.293	0.431	0.167	0.271	0.357	0.547	0.090	0.056	0.105
GS x FQ			0.089	0.046	0.056	0.533	0.055	0.063	0.551	0.426	0.276	0.931	0.535	0.308	0.317	0.097	0.046	0.732	0.530	0.638	0.998
FF x FQ			0.169	0.096	0.032	0.015	0.068	0.023	0.014	0.290	0.132	0.005	0.788	0.848	0.929	0.525	0.611	0.230	0.400	0.607	0.698
GS x FF x FQ			0.451	0.294	0.733	0.459	0.253	0.704	0.487	0.833	0.644	0.600	0.179	0.358	0.638	0.324	0.303	0.642	0.067	0.561	0.367

[a-d]Means within a column not sharing a common superscript differ ($P \leq 0.05$)
[1]GS=Genetic Strain; HY=high yielding stain; FG=fast growing strain.
[2]FF= Feed Form; C=Crumbles; P=Pellets.
[3]FQ=Feed Quality; Low and High treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of Low:High Crumbles being hand mixed for creation of the Medium Treatment; Low, Medium, and High treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% IP, respectively.
[4]Birds receiving Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.
[5]Med.=Medium FQ.
[6]Birds receiving Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.
[7]Birds receiving High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.
[8]IP=Intact Pellet.

Table 4.8 Comparisons of straight-run broiler performance for two GS[1] fed diets differing in FF[2] and FQ[3] during the starter period (d 0-18).

GS[1]	FF[2]	FQ[3]	D 18 Ending BW (kg)	D 0-18 BW Gain (kg)	D 0-18 Feed Intake/bird (kg)	D 0-18 Mortality (%)	D 0-18 FCR	D 18 CV of Ending BW (%)
Main Effects- Feed Form								
-	C	-	0.709	0.668	0.947	6.450	1.298^{b}	10.851
-	P	-	0.698	0.657	0.937	6.799	1.309^{a}	10.297
SEM			0.004	0.004	0.006	0.849	0.004	0.277
Main Effects- Feed Quality								
-	-	Low[4]	0.697	0.656	0.943	7.259	1.310^{a}	10.637
-	-	Med.[5,6]	0.705	0.664	0.952	7.186	1.306^{ab}	10.117
-	-	High[7]	0.708	0.667	0.931	5.430	1.295^{b}	10.967
SEM			0.005	0.005	0.007	1.040	0.004	0.340
Genetic Strain x Feed Form Interaction Means								
HY	C	-	0.702^{b}	0.660^{b}	0.934	4.594	1.298	10.890
	P	-	0.675^{c}	0.634^{c}	0.914	6.543	1.314	10.934
FG	C	-	0.716^{ab}	0.676^{ab}	0.960	8.306	1.299	10.811
	P	-	0.721^{a}	0.681^{a}	0.960	7.055	1.305	9.661
SEM			0.006	0.006	0.009	1.200	0.005	0.392
Genetic Strain x Feed Quality Interaction Means								
HY	-	Low	0.676	0.634	0.922	6.892	1.315	10.729
	-	Med.	0.687	0.646	0.928	5.304	1.305	10.656
	-	High	0.702	0.659	0.922	4.511	1.298	11.352
FG	-	Low	0.717	0.677	0.964	7.626	1.305	10.545
	-	Med.	0.723	0.683	0.976	9.067	1.308	9.579
	-	High	0.715	0.675	0.941	6.349	1.293	10.583
Feed Form x Feed Quality Interaction Means								
-	C	2210µm	0.712^{a}	0.671^{a}	0.950^{ab}	6.303	1.297	10.860
-		3008µm	0.710^{a}	0.669^{a}	0.972^{a}	7.480	1.307	10.511
-		3388µm	0.705^{a}	0.663^{a}	0.919^{c}	5.569	1.291	11.181
	P	40% IP[8]	0.681^{b}	0.640^{b}	0.935^{bc}	8.214	1.323	10.414
		60% IP	0.701^{ab}	0.660^{ab}	0.933^{bc}	6.892	1.305	9.724
		80% IP	0.712^{a}	0.671^{a}	0.943^{abc}	5.291	1.300	10.754
SEM			0.007	0.007	0.010	1.470	0.006	0.480
Main Effect and Interaction Probabilities								
GS			<0.001	<0.001	<0.001	0.083	0.453	0.090
FF			0.074	0.078	0.255	0.773	0.030	0.164
FQ			0.242	0.245	0.127	0.372	0.046	0.213
GS x FF			0.011	0.011	0.279	0.187	0.276	0.133
GS x FQ			0.127	0.130	0.353	0.587	0.585	0.641
FF x FQ			0.035	0.032	0.012	0.656	0.074	0.915
GS x FF x FQ			0.963	0.961	0.628	0.867	0.942	0.343

[a-c]Means within a column not sharing a common superscript differ ($P \leq 0.05$)
[1]GS=Genetic Strain; HY=high yielding stain; FG=fast growing strain.
[2]FF= Feed Form; C=Crumbles; P=Pellets.
[3]FQ=Feed Quality; Low and High treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of Low:High Crumbles being hand mixed for creation of the Medium Treatment; Low, Medium, and High treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% IP, respectively.
[4]Birds receiving Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.
[5]Med.=Medium FQ.
[6]Birds receiving Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.
[7]Birds receiving High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.
[8]IP=Intact Pellet.

Table 4.9 Comparisons of carry over effects for two GS[1] fed diets differing in FF[2] and FQ[3] during the starter period (d 0-18) and then fed common diets in subsequent growth phases (d 18-62).

GS[1]	FF[2]	FQ[3]	Ending BW (kg)			BW Gain (kg)			Feed Intake/bird (kg)			Mortality (%)			FCR			CV of Ending BW (%)		
Day/Date Range			32	46	62	0-32	0-46	0-62	0-32	0-46	0-62	0-32	0-46	0-62	0-32	0-46	0-62	32	46	62
Main Effects-Feed Form																				
-	C	-	2.022	3.553	5.034	1.981	3.512	4.993	3.081	6.292	10.908	9.887	12.229	17.494	1.454	1.697	2.020	12.015	12.283	14.537
-	P	-	2.004	3.541	4.991	1.963	3.500	4.950	3.083	6.302	10.883	11.330	14.576	18.850	1.458	1.692	2.015	12.445	12.309	14.712
SEM			0.011	0.017	0.029	0.011	0.017	0.029	0.023	0.042	0.109	1.272	1.274	1.507	0.004	0.004	0.007	0.315	0.208	0.252
Main Effects-Feed Quality																				
-	-	Low[4]	2.022	3.562	5.024	1.981	3.521	4.983	3.098	6.251	11.105	10.547	12.915	18.902	1.457	1.694	2.016	11.824	12.114	14.320
-	-	Med[5,6]	2.003	3.524	4.993	1.962	3.483	4.953	3.080	6.297	10.731	12.127	13.950	18.238	1.459	1.695	2.019	12.524	12.523	14.971
		High[7]	2.015	3.555	5.020	1.974	3.514	4.979	3.068	6.343	10.849	9.153	13.343	17.376	1.453	1.695	2.019	12.341	12.251	14.582
SEM			0.013	0.021	0.036	0.013	0.021	0.036	0.028	0.052	0.134	1.558	1.560	1.846	0.004	0.005	0.008	0.386	0.255	0.309
Genetic Strain x Feed Form Interactions																				
HY	C	-	1.964	3.451	4.983	1.922	3.409	4.941	2.987	5.999	10.364	7.602	9.639	12.242	1.458	1.690	1.982	12.812	12.664	14.752
	P	-	1.925	3.419	4.947	1.883	3.377	4.906	2.971	6.005	10.460	10.809	13.596	17.329	1.461	1.674	1.963	12.597	12.698	14.906
FG	C	-	2.080	3.655	5.086	2.040	3.615	5.046	3.176	6.585	11.452	12.173	14.818	22.747	1.451	1.704	2.058	11.218	11.903	14.322
	P	-	2.084	3.662	5.034	2.044	3.622	4.994	3.195	6.600	11.305	11.852	15.556	20.370	1.455	1.710	2.067	12.293	11.920	14.519
SEM			0.015	0.025	0.041	0.015	0.025	0.041	0.032	0.060	0.155	1.799	1.802	2.132	0.005	0.006	0.009	0.445	0.294	0.356
Genetic Strain x Feed Quality Interactions																				
HY	-	Low	1.944	3.452	4.994	1.902	3.410	4.953	3.014	6.026	10.818	11.126	13.640	19.240	1.468	1.681	1.972	12.490	12.633	14.493
	-	Med.	1.934	3.415	4.948	1.893	3.374	4.907	2.967	6.004	10.180	9.254	10.921	13.421	1.458	1.676	1.967	12.752	12.933	15.158
	-	High	1.954	3.438	4.952	1.912	3.396	4.911	2.956	5.976	10.239	7.237	10.292	11.696	1.453	1.689	1.980	12.870	12.478	14.835
FG	-	Low	2.100	3.671	5.053	2.060	3.631	5.013	3.182	6.476	11.392	9.968	12.189	18.565	1.445	1.706	2.059	11.158	11.596	14.147
	-	Med.	2.071	3.632	5.039	2.031	3.592	4.999	3.193	6.591	11.283	15.000	16.978	23.056	1.460	1.715	2.071	12.296	12.113	14.785
	-	High	2.075	3.672	5.088	2.035	3.632	5.048	3.181	6.711	11.459	11.069	16.394	23.056	1.453	1.701	2.058	11.812	12.025	14.329
Feed Form x Feed Quality																				
-	C	2210µm	2.037	3.591	5.072	1.996	3.550	5.031	3.114	6.272	11.085	8.579	10.522	15.509	1.458[ab]	1.696	2.016	11.689	11.897	14.326
-		3008µm	2.004	3.510	4.988	1.963	3.469	4.948	3.091	6.305	10.800	12.778	13.367	19.444	1.463[a]	1.700	2.029	12.099	12.570	14.762
-		3388µm	2.025	3.558	5.043	1.984	3.517	5.001	3.039	6.299	10.838	8.306	12.797	17.529	1.442[b]	1.696	2.016	12.257	12.384	14.522
-	P	40% IP[8]	2.007	3.532	4.975	1.966	3.492	4.935	3.082	6.230	11.124	12.515	15.307	22.295	1.456[ab]	1.692	2.015	11.959	12.332	14.314
-		60% IP	2.002	3.538	4.998	1.961	3.497	4.958	3.070	6.289	10.663	11.477	14.532	17.032	1.454[ab]	1.690	2.008	12.950	12.476	15.181
-		80% IP	2.004	3.551	4.998	1.963	3.511	4.957	3.097	6.388	10.860	10.000	13.889	17.222	1.464[a]	1.694	2.021	12.425	12.119	14.642
SEM			0.019	0.030	0.050	0.019	0.030	0.050	0.040	0.073	0.189	2.203	2.206	2.611	0.006	0.007	0.012	0.545	0.360	0.437
Main Effect and Interaction Probabilities																				
GS			<0.001	<0.001	0.024	<0.001	<0.001	0.022	<0.001	<0.001	<0.001	0.109	0.051	0.002	0.173	<0.001	<0.001	0.036	0.011	0.260
FF			0.252	0.617	0.293	0.254	0.623	0.296	0.959	0.863	0.870	0.452	0.197	0.527	0.431	0.394	0.580	0.338	0.931	0.626
FQ			0.581	0.421	0.807	0.587	0.423	0.809	0.758	0.463	0.135	0.404	0.896	0.843	0.624	0.968	0.955	0.417	0.517	0.330
GS x FF			0.177	0.431	0.847	0.176	0.430	0.844	0.593	0.944	0.434	0.307	0.375	0.084	0.972	0.068	0.150	0.152	0.979	0.952
GS x FQ			0.648	0.956	0.747	0.644	0.955	0.748	0.699	0.164	0.198	0.283	0.151	0.052	0.082	0.193	0.533	0.719	0.718	0.982
FF x FQ			0.759	0.359	0.577	0.760	0.358	0.577	0.475	0.651	0.877	0.494	0.636	0.192	0.031	0.845	0.499	0.801	0.602	0.880
GS x FF x FQ			0.745	0.838	0.779	0.757	0.834	0.778	0.683	0.585	0.515	0.544	0.641	0.661	0.102	0.037	0.512	0.077	0.142	0.940

[a-b]Means within a column not sharing a common superscript differ ($P \leq 0.05$)

[1]GS=Genetic Strain; HY=high yielding stain; FG=fast growing strain.

[2]FF= Feed Form; C=Crumbles; P=Pellets.

[3]FQ=Feed Quality; Low and High treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of Low:High Crumbles being hand mixed for creation of the Medium Treatment; Low, Medium, and High treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% IP, respectively.

[4]Birds receiving Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.

[5]Med.=Medium FQ.

[6]Birds receiving Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.

[7]Birds receiving High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.

[8]IP=Intact Pellet.

Table 4.10 Comparisons of d 63 processing weights and wooden breast severity for straight-run broilers of two GS[1] fed diets differing in FF[2] and FQ[3] during the starter period (d 0-18) and then fed common diets in subsequent growth phases (d 18-62).

GS[1]	FF[2]	FQ[3]	Carcass Weight (kg)	Fat Pad[4] (kg)	Drumsticks (kg)	Thighs (kg)	Wings (kg)	Pectoralis Major (kg)	Pectoralis Minor (kg)	Total Pectoralis[5] (kg)	Wooden Breast Severity
Main Effects- Feed Form											
-	C	-	3.865	0.069	0.476	0.666	0.392	1.167	0.229	1.399	1.023
-	P	-	3.869	0.071	0.476	0.670	0.393	1.166	0.225	1.388	1.162
SEM			0.025	0.001	0.003	0.005	0.002	0.010	0.002	0.012	0.061
Main Effects- Feed Quality											
-	-	Low[6]	3.909	0.070	0.478	0.676	0.398[a]	1.187	0.227	1.414	1.292[a]
-	-	Med.[7,8]	3.839	0.070	0.473	0.659	0.394[ab]	1.150	0.225	1.374	0.965[b]
-	-	High[9]	3.853	0.070	0.476	0.669	0.386[b]	1.163	0.229	1.393	1.021[b]
SEM			0.030	0.002	0.004	0.006	0.003	0.013	0.002	0.014	0.074
Genetic Strain x Feed Form Interaction Means											
HY[10]	C	-	3.851	0.066	0.456	0.642	0.378	1.234	0.234	1.472	1.435
	P	-	3.833	0.066	0.456	0.645	0.381	1.222	0.230	1.449	1.463
FG[11]	C	-	3.878	0.071	0.496	0.690	0.406	1.099	0.223	1.327	0.611
	P	-	3.906	0.076	0.495	0.695	0.405	1.111	0.220	1.326	0.861
SEM			0.035	0.002	0.005	0.007	0.003	0.015	0.002	0.017	0.086
Genetic Strain x Feed Quality Interaction Means											
HY	-	Low	3.895	0.070[bc]	0.460	0.657	0.384	1.245	0.233	1.478	1.583
	-	Med.	3.799	0.063[d]	0.451	0.628	0.381	1.205	0.227	1.438	1.319
	-	High	3.831	0.066[cd]	0.458	0.645	0.374	1.234	0.235	1.465	1.444
FG	-	Low	3.923	0.070[abc]	0.497	0.695	0.411	1.129	0.221	1.349	1.000
	-	Med.	3.878	0.077[a]	0.496	0.690	0.407	1.094	0.222	1.310	0.611
	-	High	3.875	0.074[ab]	0.493	0.692	0.399	1.092	0.222	1.321	0.597
Feed Form x Feed Quality Interaction Means											
-	C	2210µm	3.964	0.070	0.485	0.681	0.401	1.212	0.230	1.441	1.264
-		3008µm	3.797	0.068	0.472	0.648	0.389	1.141	0.228	1.373	0.875
-		3388µm	3.833	0.067	0.472	0.668	0.386	1.148	0.230	1.384	0.931
	P	40% IP[10]	3.853	0.070	0.472	0.671	0.394	1.163	0.224	1.386	1.319
		60% IP	3.881	0.071	0.475	0.670	0.398	1.159	0.222	1.375	1.056
		80% IP	3.873	0.073	0.479	0.669	0.387	1.178	0.228	1.402	1.111
SEM			0.043	0.002	0.006	0.009	0.004	0.018	0.003	0.020	0.105
Main Effect and Interaction Probabilities											
GS			0.156	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
FF			0.896	0.146	0.870	0.530	0.767	0.984	0.077	0.480	0.109
FQ			0.234	0.990	0.699	0.167	0.019	0.115	0.365	0.157	0.006
GS x FF			0.523	0.270	0.909	0.924	0.577	0.394	0.692	0.489	0.199
GS x FQ			0.831	0.023	0.722	0.386	0.975	0.657	0.286	0.904	0.458
FF x FQ			0.063	0.541	0.237	0.207	0.144	0.065	0.747	0.180	0.791
GS x FF x FQ			0.489	0.462	0.539	0.934	0.509	0.143	0.240	0.140	0.805

[a-d]Means within a column not sharing a common superscript differ ($P \leq 0.05$)
[1]GS=Genetic Strain; HY=high yielding stain; FG=fast growing strain.
[2]FF= Feed Form; C=Crumbles; P=Pellets.
[3]FQ=Feed Quality; Low and High treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of Low:High Crumbles being hand mixed for creation of the Medium Treatment; Low, Medium, and High treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% IP, respectively.
[4]Fat Pad=Abdominal Fat Pad.
[5]Total Pectoralis= Pectoralis Major + Pectoralis Minor.
[6]Birds receiving Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.
[7]Med.=Medium FQ.
[8]Birds receiving Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.
[9]Birds receiving High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.
[10]IP=Intact Pellet.

Table 4.11 Comparisons of d 63 processing yields (relative to d 62 BW and Carcass Weight) for straight-run broilers of two GS[1] fed diets differing in FF[2] and FQ[3] during the starter period (d 0-18) and then fed common diets in subsequent growth phases (d 18-62).

GS[1]	FF[2]	FQ[3]	Fat Pad Yield[4] (%)		Drumstick Yield (%)		Thigh Yield (%)		Wing Yield (%)		Pectoralis Major (%)		Pectoralis Minor (%)		Total Pectoralis[5] (%)	
Yield Relative to:			BW[6]	CW[7]	BW	CW	BW	CW	BW	CW	BW	CW	BW	CW	BW	CW
Main Effects- Feed Form																
-	C	-	1.366	1.828	9.181	12.277	12.860	17.202	7.563	10.087	22.715	30.221	4.451	5.924	27.126	36.115
-	P	-	1.419	1.901	9.195	12.259	12.909	17.274	7.591	10.123	22.693	30.268	4.406	5.861	27.120	36.165
SEM			0.026	0.036	0.041	0.053	0.069	0.089	0.028	0.040	0.122	0.144	0.029	0.037	0.129	0.147
Main Effects- Feed Quality																
-	-	Low[8]	1.376	1.838	9.181	12.200	12.920	17.258	7.600[a]	10.077[b]	22.920	30.523	4.385	5.824	27.314	36.376
-	-	Med.[9,10]	1.398	1.869	9.192	12.321	12.768	17.089	7.635[a]	10.222[a]	22.568	30.029	4.465	5.920	26.982	35.957
		High[11]	1.405	1.886	9.191	12.281	12.966	17.365	7.495[b]	10.016[b]	22.623	30.181	4.436	5.935	27.074	36.088
SEM			0.032	0.044	0.050	0.065	0.084	0.109	0.034	0.049	0.149	0.176	0.035	0.045	0.157	0.181
Genetic Strain x Feed Form Interaction Means																
HY	C	-	1.342	1.770	8.948	11.773	12.666	16.668	7.424	9.760	24.489[a]	32.136	4.633	6.070	29.064	38.148
	P	-	1.349	1.787	8.987	11.837	12.684	16.758	7.476	9.893	24.085[a]	31.859	4.599	6.047	28.704	37.947
FG	C	-	1.391	1.885	9.414	12.781	13.055	17.736	7.702	10.414	20.940[b]	28.306	4.269	5.779	25.188	34.081
	P	-	1.490	2.015	9.403	12.690	13.134	17.790	7.706	10.353	21.301[b]	28.676	4.213	5.675	25.537	34.384
SEM			0.037	0.050	0.058	0.075	0.097	0.126	0.040	0.057	0.172	0.203	0.040	0.052	0.182	0.208
Genetic Strain x Feed Quality Interaction Means																
HY	-	Low	1.388[abc]	1.839[bc]	8.935	11.737	12.704	16.817	7.464	9.824	24.307	32.128	4.565	5.996	28.870	38.155
	-	Med.	1.290[c]	1.700[c]	8.967	11.811	12.520	16.442	7.523	9.936	24.115	31.712	4.631	6.036	28.713	37.759
	-	High	1.357[bc]	1.797[c]	9.001	11.867	12.800	16.879	7.363	9.719	24.440	32.152	4.651	6.145	29.069	38.229
FG	-	Low	1.364[bc]	1.837[bc]	9.427	12.677	13.136	17.700	7.736	10.330	21.534	28.917	4.205	5.652	25.757	34.597
	-	Med.	1.506[a]	2.037[a]	9.417	12.832	13.015	17.737	7.747	10.508	21.021	28.347	4.299	5.804	25.252	34.154
	-	High	1.452[ab]	1.976[ab]	9.381	12.696	13.132	17.851	7.628	10.312	20.807	28.209	4.220	5.724	25.079	33.946
Feed Form x Feed Quality Interaction Means																
-	C	2210µm	1.355	1.804	9.179	12.215	12.841	17.124	7.591	10.032	23.169	30.755	4.375	5.792	27.450	36.465
-		3008µm	1.377	1.842	9.202	12.347	12.696	17.024	7.618	10.203	22.498	29.932	4.521	6.004	26.943	35.948
-		3388µm	1.367	1.837	9.162	12.269	13.044	17.458	7.479	10.025	22.478	29.976	4.458	5.977	26.986	35.931
-	P	40% IP[12]	1.397	1.872	9.183	12.186	12.999	17.393	7.609	10.121	22.672	30.291	4.395	5.855	27.177	36.287
-		60% IP	1.419	1.896	9.182	12.296	12.840	17.155	7.652	10.241	22.639	30.126	4.409	5.835	27.022	35.965
-		80% IP	1.442	1.936	9.219	12.294	12.889	17.272	7.512	10.006	22.769	30.386	4.413	5.893	27.162	36.245
SEM			0.046	0.062	0.071	0.091	0.119	0.155	0.049	0.069	0.211	0.248	0.049	0.064	0.223	0.255
Main Effect and Interaction Probabilities																
GS			0.012	0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
FF			0.157	0.147	0.812	0.817	0.617	0.571	0.477	0.526	0.901	0.819	0.264	0.228	0.974	0.809
FQ			0.807	0.728	0.985	0.417	0.224	0.205	0.015	0.012	0.204	0.133	0.270	0.175	0.312	0.249
GS x FF			0.216	0.261	0.672	0.279	0.751	0.887	0.551	0.091	0.029	0.115	0.793	0.441	0.055	0.231
GS x FQ			0.035	0.027	0.729	0.576	0.787	0.378	0.871	0.804	0.125	0.305	0.591	0.335	0.146	0.287
FF x FQ			0.916	0.931	0.862	0.917	0.337	0.325	0.982	0.743	0.146	0.193	0.417	0.191	0.570	0.627
GS x FF x FQ			0.184	0.187	0.272	0.476	0.345	0.242	0.901	0.981	0.035	0.037	0.422	0.757	0.069	0.075

[a-c]Means within a column not sharing a common superscript differ ($P \leq 0.05$)
[1]GS=Genetic Strain; HY=high yielding stain; FG=fast growing strain.
[2]FF= Feed Form; C=Crumbles; P=Pellets.
[3]FQ=Feed Quality; Low and High treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of Low:High Crumbles being hand mixed for creation of the Medium Treatment; Low, Medium, and High treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% IP, respectively.
[4]Fat Pad=Abdominal Fat Pad.
[5]Total Pectoralis= Pectoralis Major + Pectoralis Minor.
[6]Individual tissue weights placed on yield basis relative to d 62 individual BW.
[7]Individual tissue weight placed on yield basis relative to Carcass Weight (CW).
[8]Birds receiving Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.
[9]Med.=Medium FQ.
[10]Birds receiving Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.
[11]Birds receiving High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.
[12]IP=Intact Pellet.

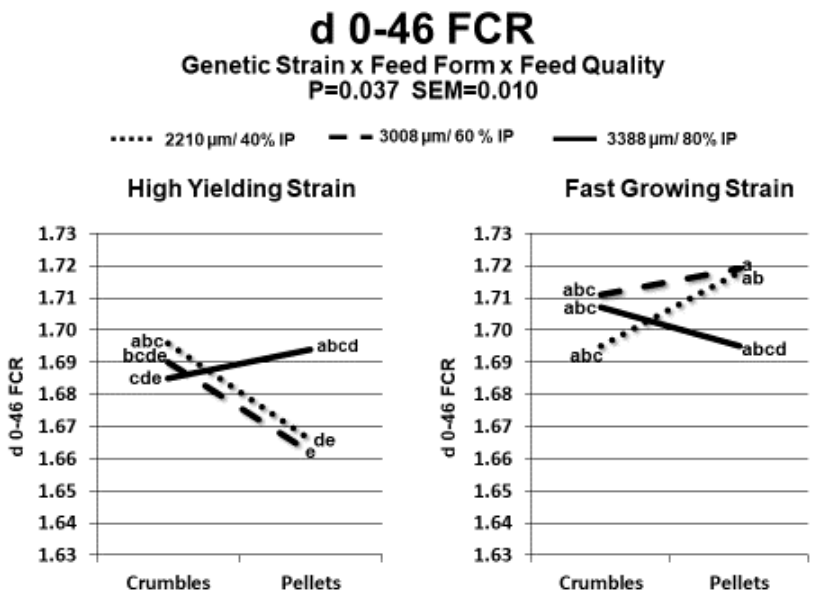

Figure 4.1 Interactive effects on d 0-46 FCR of two GS[1] fed diets differing in FF[2] and FQ[3-6] during the starter period (d 0-18) and then fed common diets in subsequent growth phases (d 18-46).

[a-e]Means within a column not sharing a common superscript differ ($P \leq 0.05$)
[1]GS=Genetic Strain.
[2]FF= Feed Form.
[3]FQ=Feed Quality; 2210 and 3388 µm treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of 2210:3388 crumbles being hand mixed for creation of the 3008 µm treatment; Treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% intact pellets (IP), respectively.
[4]Birds assigned Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.
[5]Birds assigned Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.
[6]Birds assigned High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.

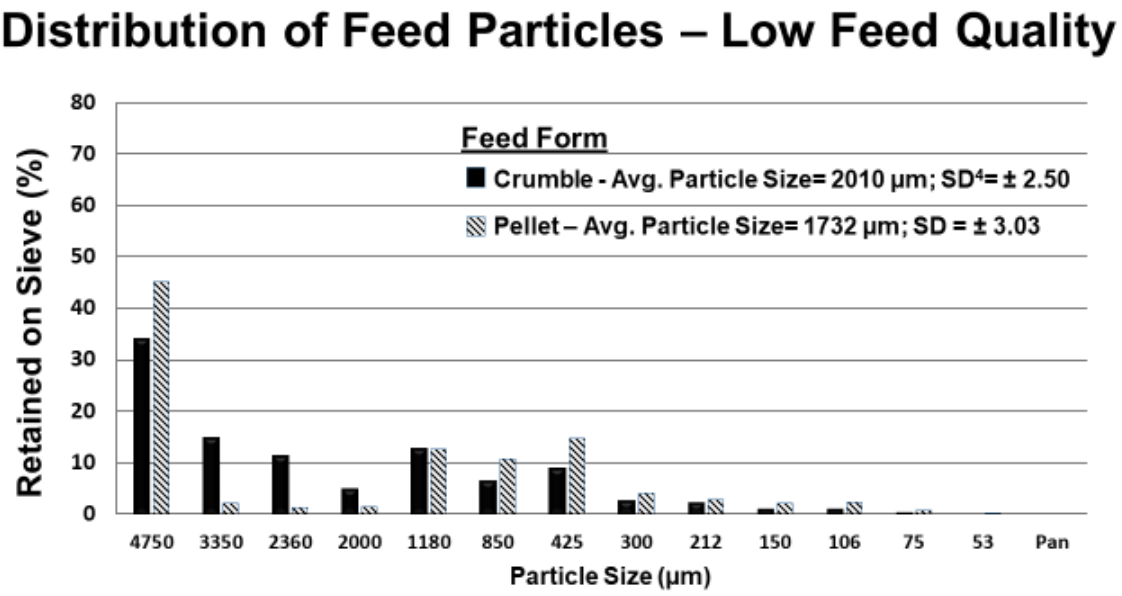

Figure 4.2 Particle size distributions for representative sample of Low FQ[1] feed for each FF[2] (crumbles or pellets) presented to two GS[3] from d 0-18.

[1]FQ=Feed Quality.
[2]FF=Feed Form.
[3]GS=Genetic Strain.
[4]SD=Standard Deviation.

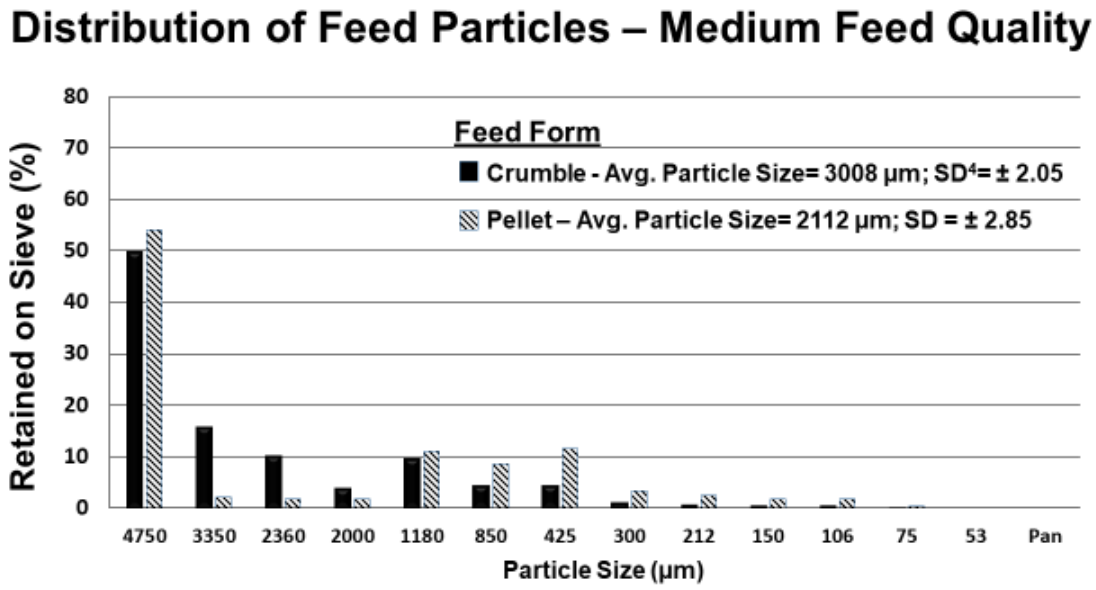

Figure 4.3 Particle size distributions for representative sample of Medium FQ[1] feed for each FF[2] (crumbles or pellets) presented to two GS[3] from d 0-18.

[1]FQ=Feed Quality.
[2]FF=Feed Form.
[3]GS=Genetic Strain.
[4]SD=Standard Deviation.

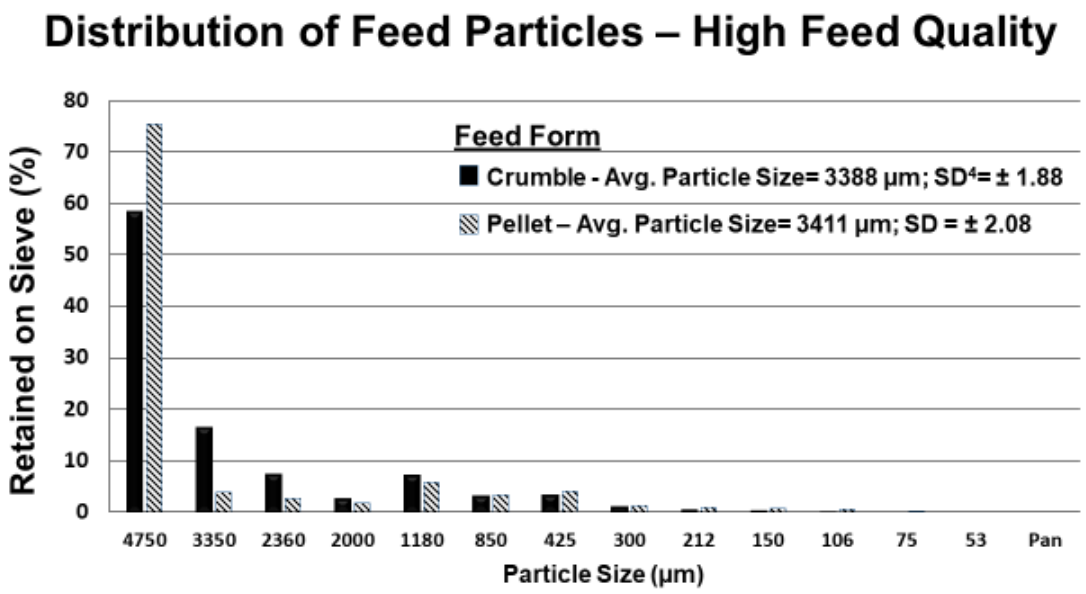

Figure 4.4 Particle size distributions for representative sample of High FQ[1] feed for each FF[2] (crumbles or pellets) presented to two GS[3] from d 0-18.

[1]FQ=Feed Quality.
[2]FF=Feed Form.
[3]GS=Genetic Strain.
[4]SD=Standard Deviation.

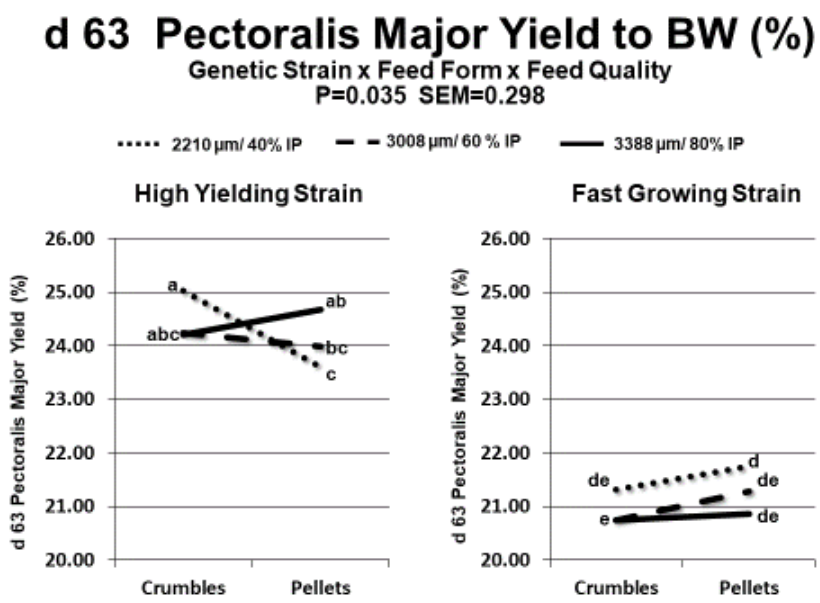

Figure 4.5 Interactive effects on d 63 pectoralis major yield (relative to d 62 BW) of two GS[1] fed diets differing in FF[2] and FQ[3-6] during the starter period (d 0-18) and then fed common diets in subsequent growth phases (d 18-62).

[a-e]Means within a column not sharing a common superscript differ ($P \leq 0.05$)
[1]GS=Genetic Strain.
[2]FF= Feed Form.
[3]FQ=Feed Quality; 2210 and 3388 µm treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of 2210:3388 crumbles being hand mixed for creation of the 3008 µm treatment; Treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% intact pellets (IP), respectively.
[4]Birds assigned Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.
[5]Birds assigned Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.
[6]Birds assigned High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.

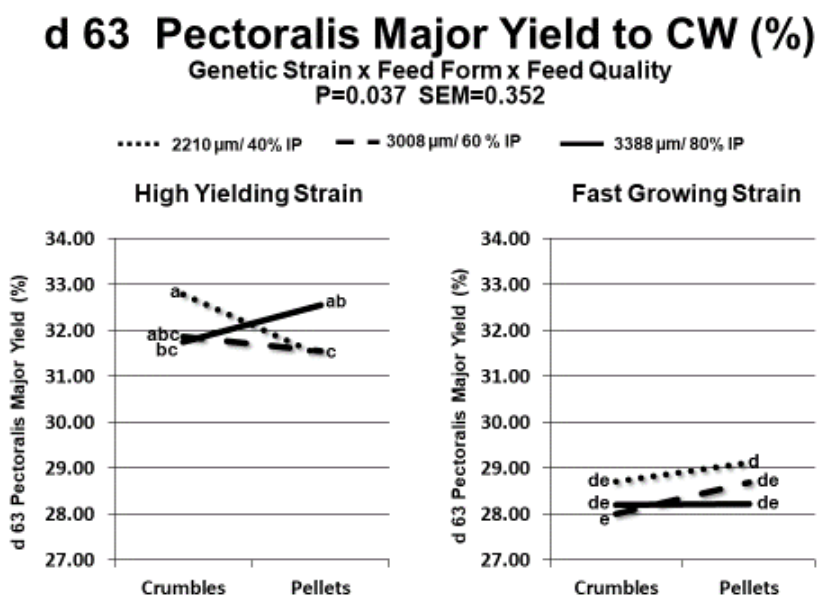

Figure 4.6 Interactive effects on d 63 pectoralis major yield (relative to CW[1]) of two GS[2] fed diets differing in FF[3] and FQ[4-7] during the starter period (d 0-18) and then fed common diets in subsequent growth phases (d 18-62).

[a-e]Means within a column not sharing a common superscript differ ($P \leq 0.05$)
[1]CW=Carcass Weight.
[2]GS=Genetic Strain.
[3]FF= Feed Form.
[4]FQ=Feed Quality; 2210 and 3388 µm treatments for the FF of crumbles were created by adjusting the gap width of a crumbler, with a 50:50 ratio of 2210:3388 crumbles being hand mixed for creation of the 3008 µm treatment; Treatments for the FF of pellets were created by adding ground pellets ("fines') to pellets in determined proportions for the creation of 40, 60, and 80% intact pellets (IP), respectively.
[5]Birds assigned Low FQ received either 2210 µm crumbles or 40% IP dependent on assigned FF.
[6]Birds assigned Medium FQ received either 3008 µm crumbles or 60% dependent on assigned FF.
[7]Birds assigned High FQ received either 3388 µm crumbles or 80% IP dependent on assigned FF.