The effect of dietary corn particle size on broiler chicken growth, development, and productivity

by
Gabrielle Harder

A thesis presented to the Honors College of Middle Tennessee State University in partial fulfillment of the requirements for graduation from the University Honors College

Spring 2022

Thesis Committee:

Dr. Kevin Downs, Thesis Director

Joseph Gulizia, Second Reader

Dr. Philip Phillips, Thesis Committee Chair

The effect of dietary corn particle size on broiler chicken growth, development, and productivity

by Gabrielle Harder

APPROVED:

____

Dr. Kevin Downs, Thesis Director
Professor, School of Agriculture

____

Dr. Philip Phillips, Thesis Committee Chair
Associate Dean, University Honors College

ACKNOWLEDGMENTS

I would like to express my deepest appreciation to my thesis advisor, Dr. Kevin Downs. His guidance has been invaluable throughout my exploration in an unfamiliar field of study, making my research possible. I would like to extend my sincere thanks to Joseph Gulizia for lending his knowledge as my second reader and assistance with statistical analysis. I also wish to thank Santiago Sasia and Dr. Wilmer Pacheco of Auburn University for sharing their expertise. I would like to acknowledge the MTSU Honors College for providing the opportunity to complete this project, which has been an invaluable learning experience. Lastly, I am grateful for my mom and dad who have provided their unconditional love and support throughout this journey. I would like to express my appreciation to Isabelle Bisio for her uplifting late-night discussions and absolute belief in my success.

ABSTRACT

Improving poultry feed can lead to numerous economic benefits, including increased feed milling efficiency, reduced energy expenditures, decreased production costs, and reduced consumer prices. The particle size of corn is a main consideration in broiler chicken diet manufacturing, as a significant portion of feed cost is allotted to grinding of corn. Two identical trials were conducted to assess the impact of varying corn particle size (CPS) on broiler performance, organ development, and nutrient digestibility. Both experiments included three dietary treatments, differing only in CPS (832, 1432, or 2036 µm). In trial 1, CPS influenced feed conversion ratio (FCR), with the 2036 µm treatment being higher than the 832 µm treatment between d 1 and 7 ($P=0.018$), while body weight (BW) and feed consumption (FC) were not affected ($P>0.05$). In trial 2, there were differences observed for d 1 to 7 and d 1 to 14 BW ($P<0.05$), with BW increasing as CPS decreased. There were no observed impacts on FC or FCR during any period ($P>0.05$). In both experiments, CPS influenced proventriculus absolute weights, with the largest weights corresponding to birds fed the smallest CPS. No differences were noted for crop or gizzard data ($P>0.05$). There were no treatment effects on apparent ileal digestible energy (AIDE), digestible crude protein (CP), fat, or phosphorus (P) for either trial. Both trials demonstrated treatment differences for digestible calcium (Ca), with digestibility reduced for the smallest CPS ($P<0.05$). These data indicate varying corn particle size in crumbled broiler starter diets minimally altered early bird performance.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

REVIEW OF LITERATURE

Development of Commercial Livestock and Poultry Feed Manufacturing

With the domestication of livestock, animal husbandry became an essential aspect of human life. Historically, livestock species, including poultry, were allowed to free-range and graze. Once the focus shifted from small family farms to commercial farming operations, animals were raised for greater productivity and improved performance. This led to advancements in agricultural production. With further understanding through nutritional studies, an emphasis on diet composition encouraged the development of the feed industry (Coffey et al., 2016).

There are numerous benefits to commercial manufacturing of animal feed, including the ability to meet the nutritional requirements of poultry and livestock species. This can be achieved through enhanced nutrient availability and digestibility (van der Poel et al., 2020). There are many aspects to manufacturing quality animal feed, including balanced amounts of essential nutrients to form a complete diet, physical characteristics of the feed, and processing techniques (Kiarie and Mills, 2019).

Significant attributes of feed physical structure depend on ingredients and processing methods. Physical size of ingredient particles is altered through physical grinding. Grinding is used to reduce particle size by exerting force on the physical structure of ingredients (Lyu et al., 2020). The predominant grinding methods involve roller mills and hammermills (Figures 1 and 2) (Lyu et al., 2020). Roller mills contain rolls that produce a compression force if rotating at the same speed, or a combination of shearing and compression forces if rolls rotate at different rates. Hammer mills consist of multiple hammers that directly impact feed particles for size reduction (Koch, 2002). Roller mills have advantages over hammer mills, including greater energy efficiency and quieter operation. The slower operating speeds of the rolls do not generate heat, diminishing energy loss. Roller mills also allow for more consistent distribution of particle sizes, permitting more exact control of particle size with fewer fine fractions (Koch, 2002; Lyu et al., 2020). However, roller mills pose some disadvantages, including a high initial purchasing cost and production of irregular particles with a more rectangular shape, rather than spherical (Koch, 2002). Roller milling also has limited ability to reduce fibrous particles due to minimal tearing action (Lyu et al., 2020). Hammer mills are preferred with fibrous feedstuffs and a greater range of ingredient sizes are desired (Koch, 2002). Hammer mills have lower initial costs and maintenance is less expensive, though they are less energy efficient, have increased noise disturbance, and create dust pollution (Koch, 2002). Although grinding is a key step in feed manufacturing, there are concerns associated with excessive grinding and size reduction, such as wasted energy, increased production costs, and the potential for digestive issues in animals, including gastric ulcers in swine and underdeveloped gizzards in poultry (Koch, 2002; Kiarie and Mills, 2019).

Another critical step in the feed manufacturing process is mixing. This involves combining different ingredients (feedstuffs) and feed additives to produce a final homogenized feed product (Kairie and Mills, 2019). Proper mixing is vital to ensure nutrient uniformity, adequate particle size distribution, and reduced segregation of feed ingredients (Behnke, 1996; Kiarie and Mills, 2019; Lyu et al., 2020).

In feed manufacturing, hydrothermal treatments are used to reduce prevalence of harmful microbes and improve nutrient availability (Kiarie and Mills, 2019; Lyu et al., 2020). The purpose of these processes is to aggregate smaller particles into larger ones. This is accomplished through a combination of compression, heat, and moisture (Kiarie and Mills, 2019). During the conditioning phase, high pressure steam supplies the moisture and heat necessary for gelatinization of starch, improving starch digestibility and enhancing pellet binding (Muramatsu et al., 2015). High temperatures during conditioning further function to eliminate feed pathogenic bacteria, such as *Salmonella* spp., and meet hygiene standards (Abdollahi et al., 2020).

Heat application involved in the conditioning process can significantly affect feed components. Temperatures of this treatment can cause the degradation of the three-dimensional structure of feed ingredients, including proteins and starch (Svihus, 2006). Starch gelatinization involves the permanent loss of starch granule crystallinity within the structure (Teixeira Netto et al., 2019). This change allows better accessibility to the starch surface, improving interactions with enzymes. Heat denaturation of dietary protein tertiary structure permits better access for proteases, improving protein digestibility (Teixeira Netto et al., 2019). There are also some potential negative ramifications to heat treatment. Vitamins and added enzymes are vulnerable to denaturation (Svihus, 2006). A potential issue occurring with heat processing is the occurrence of the Maillard reaction. The bioavailability of free basic amino acids, such as lysine and glycine, is lowered as they react with reducing sugars to produce unusable Maillard reaction products (van Soest and Mason, 1991).

Hydrothermal processing affects the macrostructure of feed, which refers to properties of feed form, such as mash or pellets. In poultry, mash feed is commonly utilized for broiler breeders and table egg laying hens. Broilers and other poultry are often fed pelleted feed (Svihus, 2006). Mash is a form of feed with ingredients finely ground (400 to 650 μm) and uniformly mixed (Jafarnejad et al., 2010). Pellets are formed by mechanically compressing mash feed into larger sized pellets (Abadi et al., 2019). Additionally, the pelleting process causes microstructures to be more refined as the size of particles is reduced due to the grinding action in the pellet mill (Svihus, 2006). Pelleting is commonly utilized in the poultry industry and presents numerous benefits and economic advantages. Pelleted diets allow for the inclusion of wider varieties of ingredients and utilization of alternative feedstuffs, as well as increased nutrient density (Behnke 1996). Pelleted diets improve feed intake compared to mash diets, as feed intake is primarily determined by feed macrostructure (Svihus, 2006). A proposed explanation for this feeding behavior is hyperphagia, excessive feed consumption due to an increased appetite (Nir et al., 1995). Mechanoreceptors in the beak compensate for poorly developed senses of taste and smell in the bird (Herrera et al., 2017). The sensory inputs from changes in size and texture of pelleted feed particles to the mechanoreceptors influence feeding behaviors (Nir et al., 1995). Enhanced feed consumption with a decreased prevalence of selective feeding also reduces the amount of feed wasted, improving feed conversion (Behnke, 1996; Abadi et al., 2019; Kiarie and Mills, 2019). Another feed form is crumbles, where pelleted diets are further crushed into a texture coarser than mash, which is more appropriate for chicks (Jafarnejad et al., 2010).

Feed Particle Size in Poultry

Feed particle size significantly impacts organ development of the poultry digestive tract. However, the effects of particle size are often ingredient dependent, and digestion of certain nutrients varies. While poultry are considered monogastric, they possess distinct gastrointestinal tract characteristics. Major components of the poultry digestive tract include the crop, proventriculus, gizzard, small intestine, large intestine, and ceca. The crop is a storage organ that holds feed after swallowing, the usage of which is dependent on bird feeding habits (Svihus, 2014). Digestion of feed also begins in the crop with digestive enzymes secreted from the mouth (Svihus, 2014). The glandular stomach of the poultry gastrointestinal (GI) tract is the proventriculus. Hydrochloric acid is secreted, and pepsinogen is cleaved to form the enzyme pepsin, which is incorporated into the feed mixture in this organ. The gizzard is a muscular organ that functions to grind feed, as birds cannot reduce the size of feed particles by mastication (Svihus, 2014; Kiarie and Mills, 2019). Digesta flux between the proventriculus and gizzard increases retention time, aiding in protein digestion (Svihus, 2014). The majority of absorption of nutrients occurs in the small intestine. The first section of the small intestine is the duodenal loop, where the gizzard contents are combined with bile and enzymes secreted by the pancreas (Svihus, 2014). Following the duodenal loop is the jejunum, the major site of nutrient absorption and location of fat degradation (Svihus, 2014). Proceeding the Meckel's diverticulum, a residual sac formed during embryonic development, is the start of the ileum (Svihus, 2014). The ileum is a crucial site for mineral and water absorption and ends at the ileo-colonic-cecal junction (Svihus, 2014). At the ileum and colon juncture, a pair of sacs called ceca are present. These structures are crucial for fermentation of undigested nutrients, electrolyte absorption, and water absorption (Svihus, 2014).

The sizes of grain particles in diets formulated for geese are significant deliberations in commercial geese production. Diets containing whole grains have shown positive effects on performance. In studies utilizing rice in early gosling diets, the inclusion of whole rice was noted to increase weight gain and decrease feed conversion ratio compared to crushed rice (Wang et al., 2014; Fu et al., 2021). Fu et al. (2021) suggests these observations are explained by improved gastrointestinal tract functionality due to stimulation from coarse rice particles. Conflicting results were reported for the influence of whole rice on daily feed intake. In the early starter phase using crumbled diets, feed intake was improved by wholegrain rice, potentially due to improved palatability from increased starch gelatinization during manufacturing (Fu et al., 2021). Whole grain inclusion typically stimulates the development of the gastrointestinal tract, notably the gizzard. In both studies, however, this was not demonstrated when geese were fed mash or pelleted feed with whole grain rice (Wang et al., 2014; Fu et al., 2021). Assessment of carcass characteristics exhibits minimal influence from rice particle size, possibly due to no differences in feed intake between treatments (Wang et al., 2014; Fu et al., 2021).

When considering the numerous feed ingredients in diets of table egg layers, particle size of the cereal grain base and calcium additives are significant focuses. However, it is important to note that many studies have observed a greater influence on performance characteristics for feed form rather than dietary particle size (Bozkurt et al., 2020). In laying hens, larger particles of wheat, barley, and maize (corn), significantly increased voluntary feed intake (Safaa et al., 2009; Herrera et al., 2017). Hens prefer coarse particles as such sizes are better suited to the dimensions of the beak and oral cavity, maximizing feed intake (Mtei et al., 2019). Coarsely ground diets, however, encourage selective feeding, which may negatively impact feed efficiency (Herrera et al., 2017). Feed particle size has little impact on egg quality in commercial laying hens, where no influence was noted for egg weight or eggshell thickness (MacIsaac and Anderson, 2007; Safaa et al., 2009; Herrera et al., 2017). A possible concern discussed in multiple studies is the potential for large amounts of fine particles in diets utilizing coarser grinding (Safaa et al., 2009). A preference for coarse particles would result in the accumulation of fines at the bottom of feeders, causing unbalanced nutrient ingestion and possibly reducing egg weight and quality (Herrera et al., 2017). Specifically, vitamins, minerals, and some amino acids are often concentrated in fine fractions (Safaa et al., 2009; Herrera et al., 2017).

As laying hens have substantial calcium requirements and changes in calcium metabolism during egg production, the optimal particle size of calcium is a highly researched area in table egg layer nutrition. While there are many sources of calcium available for use in hen diets, particle size of the source may be the greater factor in eggshell quality (Saunders-Blades et al., 2009). Larger calcium particles have a longer retention time in the upper digestive tract, namely the gizzard (Pizzolante et al., 2009; Saunders-Blades et al., 2009; Saki et al., 2019). A longer retention time lowers the mineral's solubility in the digestive tract and a more gradual release of calcium (Pizzolante et al., 2009; Saki et al., 2019). This increases calcium availability, especially at night during eggshell formation, leading to better calcium absorption and improved eggshell quality (Pelicia et al., 2009; Pizzolante et al., 2009; Saunders-Blades et al., 2009; Saki et al., 2019). Additionally, improved calcium availability decreases calcium and phosphorus mobilization from bone reserves, which may positively affect bone quality (Saki et al., 2019). However, in studies comparing particle size of calcium sources, few effects on eggshell characteristics were observed. Improved eggshell strength, lower egg loss due to damaged shells, and increased shell weight were observed when coarse calcium particles were supplied (Lichovnikova, 2007; Pizzolante et al., 2009; Saki et al., 2019). There was no effect of calcium particle size on egg production, egg weight, or egg loss percentage (Pizzolante et al., 2009; Cufadar et al., 2011; Saki et al., 2019).

Calcium supplementation is also consequential in broiler breeder production. The effects of calcium particle size in these birds are similar to those observed in table egg layers (Manangi et al., 2018). However, there are distinctions owing to lower egg production. Comparable to laying hens, larger sized calcium particles are retained longer in the gizzard, reducing solubility and allowing a slow and uniform release of calcium (Bueno et al., 2016; Manangi et al., 2018). A source of dietary calcium should be constantly available for eggshell calcification to avoid excess bone calcium mobilization (Manangi et al., 2018). A dependency on calcium from bone reserves for eggshell formation decreases the amount deposited in the shell, resulting in a weakened shell (Bueno et al., 2016). Alterations to eggshell thickness and strength may affect embryo development and hatchability, which are important in broiler breeder production. Thinner shells increase embryo mortality from evaporative loss and dehydration during incubation (Bueno et al., 2016). Furthermore, a decreased need for skeletal calcium reduces the amount of phosphorus loss generated from the demineralization of bone (Manangi et al., 2018). Ultimately, a reduction of bone mobilization due to larger calcium particles improves bone strength (Bueno et al., 2016).

In broilers, like all poultry, smaller feed particle sizes negatively affect gastrointestinal tract development. This is observed most frequently in the foregut, including the proventriculus and gizzard. Diets with fine particle sizes and little structural components result in gizzard dysfunction and an enlarged proventriculus (Kiarie and Mills, 2019). As the function of the gizzard is to grind feed, it is less effective when finer particles are included in the diet (Abadi et al., 2019; Kiarie and Mills, 2019). Coarser particle sizes lead to increases in gizzard size and weight (Parsons et al., 2006; Amerah et al., 2008; Ruhnke et al., 2015; Zaefarian et al., 2016; Kiarie and Mills, 2019; Liermann et al., 2019). Larger particles require increased grinding activity, encouraging the development of gizzard muscles and resulting in larger organ size (Zaefarian et al., 2016). Additionally, greater digesta content is observed in the gizzard of birds fed diets containing coarsely ground ingredients, which further stimulates increased organ sizes (Amerah et al., 2008). Large particles reduce the pH of gizzard contents, likely due to elevated production of hydrochloric acid by the proventriculus. Coarse particles encourage gastric reverse peristalsis, intestinal contractions that permit movement of digesta, which increases the secretion of hydrochloric acid (Zaefarian et al., 2016).

Additionally, feed particle size has been observed to affect bacteria populations in the gizzard and ceca of broilers. In a study conducted by Huang et al. (2006), broilers consuming a coarse mash diet experienced higher mortality of *Salmonella typhimurium*. This increased bacterial death rate likely resulted from a progressively acidic gizzard environment, encouraged by lower pH of gizzard contents (Huang et al., 2006). Another study found broilers fed diets with coarse particle sizes had greater *Lactobacilli* spp. populations in the ceca, a species of beneficial bacteria, and lower *Clostridium* spp. numbers (Abadi et al., 2019). The increased retention time of coarse particles in combination with the reduced pH of gizzard digesta from hydrochloric acid production demonstrates an antimicrobial effect. Pathogenic bacteria present in the feed are more likely to be inactivated by the acidic gizzard environment (Jacobs et al., 2010; Abadi et al., 2019). The particle size of feed has also been demonstrated to influence nutrient digestibility. Naderinejad et al. (2016) observed improved starch digestibility and increased digestibility of calcium when coarsely ground gains were included. This is attributed to enhanced gizzard function, allowing particle size reduction of feed and subsequent digestion (Naderinejad et al., 2016). A noticed increase in feed intake and body weight in birds consuming a coarse particle diet may result from improved nutrient digestibility (Abadi et al., 2019).

Corn Particle Size in Poultry

The primary grain base for animal feed in the U.S. is corn, which comprises 95% of all feed manufacturing and usage (USDA, 2021). Corn is high in energy, with metabolizable energy values ranging from 3350 to 3900 kcal/kg, and is easy for most agricultural animals, including poultry, to digest (Jacob, 2022). In attempts to decrease feed costs in poultry production, targeting optimal particle size of corn is important. Utilizing larger corn particle sizes decreases the amount of grinding required in the manufacturing process, thus reducing costs (Rubio et al., 2020). Research has been conducted on various poultry species to assess the influences of feed corn particle size.

In young geese fed experimental diets containing ground or whole corn, effects were noted for feed intake, body weight, and feed conversion ratio during the different growth periods. Feed intake of birds fed whole corn feed was lower overall than that of birds consuming ground corn diets. Early weight gain also decreased for birds on the whole corn diet, while later body weight was unaffected from 29 to 70 days of age (Lu et al., 2011; Lu et al., 2013). These influences were attributed to the difficulty young birds had swallowing the whole corn diet during the first few days (Lu et al., 2011). Feed conversion ratio improved for birds on the whole corn treatment from 50 to 70 d of age but was not affected during other periods (Lu et al., 2011). Gizzard relative weights were greater for birds consuming whole corn diets (Lu et al., 2011; Lu et al., 2013). Minimal effects were observed for nutrient digestibility between treatments, with no differences in retention for calcium or phosphorus (Lu et al., 2011; Lu et al., 2013).

In laying hens, corn particle size had few influences on performance variables and nutrient utilization. Minimal differences were detected for body weight among treatments, except for greater body weight for hens consuming coarsely ground corn at 52 weeks. This may be attributed to the tendency for higher feed intake when birds were fed coarse corn particles (Ege et al., 2019). Performance parameters, including egg production and egg weight, were not affected by corn particle size. The treatment including coarse corn particles resulted in higher gizzard weight, but did not affect crop or proventriculus weights (Ege et al., 2019). However, Mtei et al. (2019) observed coarsely ground diets increased proventriculus absolute weights. Most mineral components in the eggs were not affected by particle size, including calcium, magnesium, zinc, copper, and manganese (Hafeez et al., 2015). In this study, the inclusion of coarse corn particle sizes with a dMEAN above 1.8 mm resulted in a greater eggshell weight and thickness, likely from the increased apparent ileal digestibility of magnesium (Hafeez et al., 2015). Magnesium is important in eggshell formation and quality, as this nutrient is deposited in small amounts throughout the shell structure (Shen and Chen, 2003). Additionally, ileal starch and calcium digestibility were also improved in laying hens consuming coarsely ground corn (Mtei et al., 2019).

Corn Particle Size in Broilers

Effects of corn particle size on organ development in broilers have been documented, with many of the same influences observed for feed particle sizes. Birds consuming finely ground corn particles tend to drink increased quantities of water to aid in swallowing, often manifesting a fluid-filled crop. As excessive water consumption is associated with incidences of pendulous crop, the likelihood of this condition developing increases (Zaefarian et al., 2016).

Dietary corn particle size has been observed to impact gut microflora. Lower digesta pH in the proventriculus and gizzard were recorded when feeds containing coarser corn particles were provided. Coarser corn consumption stimulates proventricular secretion of hydrochloric acid, creating an acidic environment that suppresses harmful bacteria in the gut, including those present in the feed (Zaefarian et al., 2016; Kiarie and Mills, 2019). This corn particle size effect can reduce the growth of *Clostridium perfringens* in the digestive tract, the principal cause of necrotic enteritis, an economically significant disease in the poultry industry (Kiarie and Mills, 2019). When coarse corn particles are included in broiler diets, the population of beneficial bacteria species *Bifidobacteria* and *Lactobacilli* increase, while the number of disease-causing

Clostridium spp. decreases (Jacobs et al., 2010; Singh et al., 2014). *Lactobacilli* populations are favorable as they can prevent the growth of pathogens such as *Salmonella* (Jacobs et al., 2010; Singh et al., 2014).

The impact of corn particle size on nutritional quality and digestibility is associated with increased surface area of finer ground particles. This allows for greater interactions with both endogenous and exogenous digestive enzymes (Zaefarian et al., 2016; Ege et al., 2019). Coarse particles increase the retention time of feed in the GI tract, increasing digestibility and absorption of nutrients and potentially improving energy utilization (Amerah et al., 2008; Hafeez et al., 2015; Rubio et al., 2020). Furthermore, enhanced digestive tract development associated with larger particles indicates feed might be held in the upper portions of the digestive tract for a greater time, permitting improved enzymatic digestion, increased starch digestibility, and possibly increasing feed efficiency (Parsons et al., 2006; Amerah et al., 2008). Stimulation of gizzard mechanical activity by coarse corn particles results in increased grinding of feed into smaller particles present in the intestinal digesta, resulting in improved digestion of dietary components (Amerah et al., 2008; Lu et al., 2011; Ruhnke et al., 2015). Additionally, adequate gizzard development encourages an increase in secretion of cholecystokinin, a hormone that stimulates the release of bile and secretion of pancreatic enzymes. A lower proventriculus and gizzard pH increases enzymatic activity of pepsin and enhances protein digestion. The inactive precursor pepsinogen is converted to pepsin in the presence of hydrochloric acid (Amerah et al., 2008). Improved protein digestion and amino acid absorption can benefit GI tract health by reducing pathogens in the lower digestive tract. Large amounts of undigested proteins and unabsorbed amino acids present in the ceca can produce adverse metabolites, including amines and ammonia, which are toxic and increase the pH of cecal content. This rise in pH allows pathogenic bacteria to proliferate (Kiarie and Mills, 2019).

Corn particle size can influence broiler growth and productivity; however, research results have been inconsistent (Table 1). Parsons et al. (2006) reported increased feed intake and feed conversion as corn particle size increased. Amerah et al. (2008) showed decreased feed intake, increased body weight gain, and improved feed conversion ratio with coarse grinding of corn. In two out of three trials, Jacobs et al. (2010) concluded that weight gain and feed efficiency generally decreased as corn particle size increased, while feed intake was not influenced by particle size in any trial. Singh et al. (2014) detected increases in feed intake and weight gain associated with increasing inclusion of coarse corn particle size. Rubio et al. (2020) reported no observed effects on body weight gain, feed intake, and feed conversion ratio during the starter and grower periods. During the finisher period, feed intake increased when a coarsely ground diet was fed. In previous reports, corn particle size did not substantially impact carcass yield but did influence breast meat weight, which decreased as particle size increased (Parsons et al., 2006; Singh et al., 2014; Lv et al., 2015).

This research evaluates the influence of varying corn particle sizes (832, 1432, and 2036 μm) included in a broiler starter diet on body weight, feed consumption, feed conversion, organ weights, and nutrient digestibility.

Table 1. Summary of the effects of increasing coarse corn particle size in broiler diets.						
Authors	**Feed Intake**	**Body Weight Gain**	**Feed Conversion Ratio**	**Gizzard Weights**	**Diet CPS**	**Diet Form**
Parsons et al. (2006)	Increase	N/A	Decrease	Increase	781, 950, 1,042, 1,109, and 2,242 µm	Mash
Amerah et al. (2008)	Decrease	Increase	Decrease	Increase	Fine (297 µm) and Coarse (528 µm)	Pelleted
Jacobs et al. (2010)	Not affected	Decrease	Decrease	Increase	557, 858, 1,210, or 1,387 µm	Mash
Singh et al. (2014)	Increase	Increase	Increased with inclusion up to 300 g/kg, then decreased	Increase	Increasing inclusion of coarse corn (1,695 µm)	Mash
Rubio et al. (2020)	Not affected	Not affected	Not affected	N/A	Starter period (0-14 D): 674, 741, 805, and 912 µm Grower period (14-28 D) 629, 763, 814, and 1,779 µm	Starter period – crumbles Grower - pelleted
Lv et al. (2015)	Increase	Increase	Not affected	Not affected	573, 865, 1,027 µm	Mash

Figure 1: Roller Mill Design (Koch, 2002).

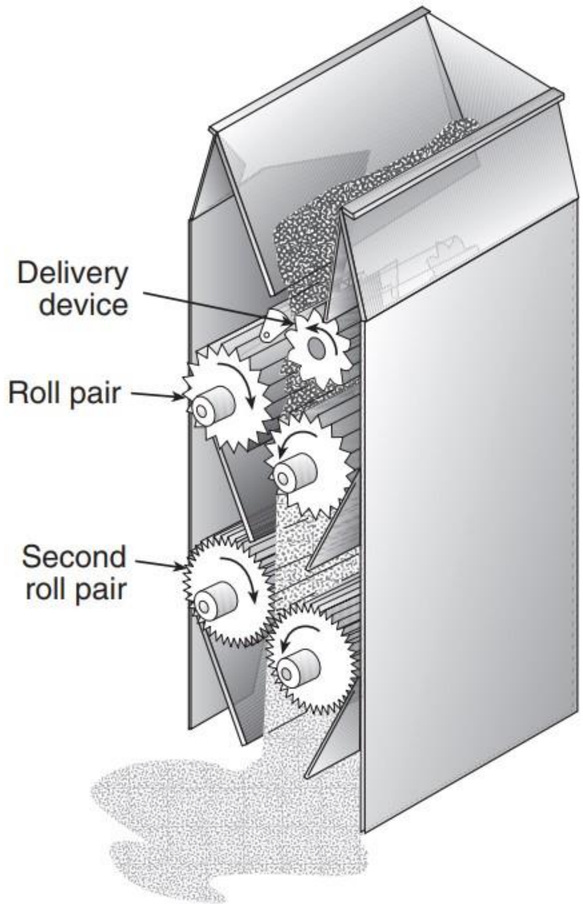
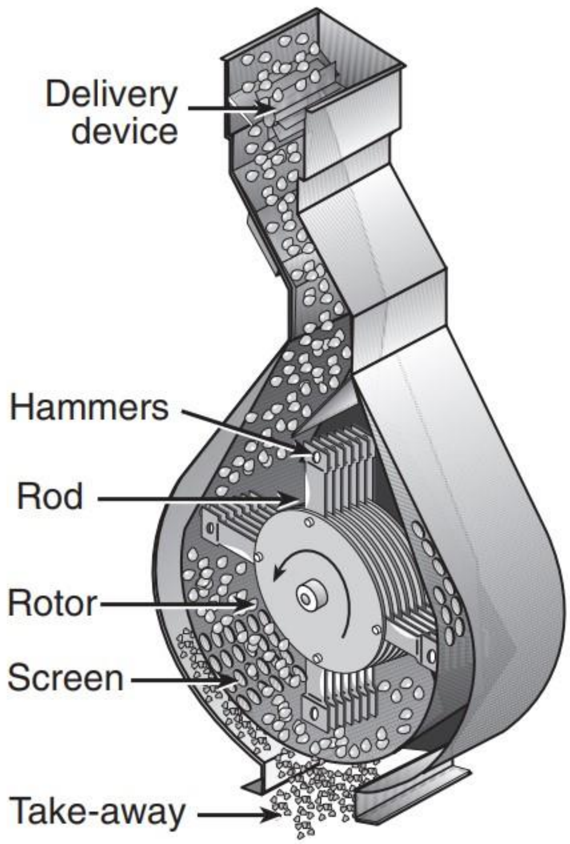


Figure 2: Hammermill Design (Koch, 2002).



CHAPTER II

DESCRIPTION OF PROBLEM

In poultry feed manufacturing, corn grinding is a significant cost center. Grinding is a standard procedure to efficiently reduce particle size of feed ingredients. This enhances digestion and nutrient utilization by increasing ingredient surface area available for interaction with digestive enzymes (Lyu et al., 2020). Particle size of feed ingredients can affect nutrient digestibility, gastrointestinal health, organ development, and bird performance (Zaefarian et al., 2016). Coarse particle sizes increase retention time of feed in the digestive tract, improve starch and calcium digestibility, and increase gizzard weight (Parsons et al., 2006; Zaefarian et al., 2016; Rubio et al., 2020). Larger particles require increased grinding activity, encouraging gizzard development.

With corn being the principal ingredient in poultry feeds, corn particle size has been considered as a potential feed manufacturing cost center expenditure reduction. Smaller corn particle sizes have a greater surface area, increasing interactions with digestive enzymes and improving feed utilization (Parsons et al., 2006; Kiarie and Mills, 2019; Rubio et al., 2020). Diets with fine corn particle sizes and a lack of structural components result in gizzard dysfunction and enlarged proventriculus, negatively affecting feed efficiency and gastrointestinal health (Jacobs et al., 2010; Kiarie and Mills, 2019; Rubio et al., 2020).

To sustain availability of chicken meat as a nutritious food source, producers seek to improve feed manufacturing processes for increased feed efficiency and decrease production costs. Utilizing larger corn particle sizes decreases the amount of grinding required in the manufacturing process, thus reducing feed costs (Rubio et al., 2020).

Studies have assessed the impact of corn particle size (CPS) on broiler performance (Xu et al., 2017; Mtei et al., 2019; Rubio et al., 2020). However, the results have been inconsistent, owing to differences in experimental factors, feed form, and a broad range of particle sizes. Xu et al. (2017) observed improved feed intake and FCR with coarse CPS, while Mtei et al. (2019) only noted increased feed intake. Rubio et al. (2020) reported no observed CPS effects on BW, FI, and FCR during the starter and grower periods. As such, two replicate trials were conducted to evaluate the influence of varying corn particle size during the starter phase on broiler performance, organ weights, and nutrient digestibility.

CHAPTER III

MATERIALS AND METHODS

All animal handling procedures for this study were approved by the Middle Tennessee State University Institutional Animal Care and Use Committee under protocol 21-2001.

Husbandry and Experimental Design

In two identical trials, 288-day-old male Cobb 700 byproduct chicks were obtained from a local hatchery (576 birds total for both trials). Chicks were randomly assigned to 18 battery brooder cages, with 6 replicate cages per treatment (16 birds per cage; 494 cm^2/bird). Treatments were randomly assigned to each cage (3 treatments, 96 birds/treatment). Birds had access to feed (9.6 cm^2/bird) and water (4.8 cm^2/bird) without restriction and were kept under continuous lighting (24 L:0 D). Battery cages were kept at 35°C and reduced on a schedule of approximately 3°C every 7 days.

Treatments consisted of three experimental crumbled diets differing in CPS (832, 1432, and 2036 μm). Diets were a standard broiler starter formulation manufactured at the Auburn University Animal Nutrition Center (Table 2). The only difference between experimental diets was CPS. Feed was manufactured approximately 7 ± 1 d prior to study initiation. To create different CPS treatments, whole corn was ground using a two pair roller mill (Roskamp Champion Series 900-12, CPM Roskamp Champion, Waterloo, IA) at three different settings. Feed ingredients were blended for 150 s (30 s dry cycle and 120 s wet cycle) using a twin shaft mixer (Model 726, Scott Equipment Co., New Prague, MN) to produce the mash diets. Additionally, phytase was premixed with 4.54 kg of ground corn using a countertop mixer (Model A-200, The Hobart Mfg. Co., Troy, OH) prior to its addition to the whole batch of feed. Diets were conditioned at 77°C for 40 seconds and pelleted through a 4.0-mm pellet die using a pellet mill (Model 1112-4, California Pellet Mill Co., Crawfordsville, IN). Pellets were dried and cooled with ambient air using a counter-flow pellet cooler (Model CC0909, California Pellet Mill Co., Crawfordsville, IN). Starter feed was crumbled in a crumbler with manual roll adjustment (Model 624SS, California Pellet Mill Co., Crawfordsville, IN). During feed manufacture, feed samples were collected at evenly spaced intervals for nutrient analysis. Additionally, an indigestible marker (0.5% titanium dioxide, TiO_2) was added to the starter feed for determination of apparent ileal nutrient digestibility.

Data Collection

Total bird weight per cage was recorded at 7-day intervals to determine average body weight (BW). Cumulative feed consumption (FC) was calculated and used in determination of feed conversion. Feed conversion ratio (FCR) was calculated by dividing the amount of feed consumed by BW gain. Mortality was monitored daily and used to adjust feed conversion.

On day 21, 6 birds/cage were euthanized via CO_2 narcosis combined with cervical dislocation to assess crop, proventriculus, gizzard, and ceca weights. Crops were removed at the end of the cervical esophagus. Proventriculus were excised at the end of the cervical esophagus and the proventricular-gizzard junction. Gizzards were removed at the proventricular-ventricular junction and the gizzard-duodenal loop junction, opened, koilin lining removed, and rinsed free of digesta. Ceca were extracted at the ileo-colonic-cecal junction. Ileal digesta was collected by gently squeezing the contents from the section of the gastrointestinal tract 1 cm proximal to the Meckel's diverticulum to the ileal-cecal junction. Digesta samples collected from each cage were combined, frozen, lyophilized, and ground. Samples were commercially analyzed for fat, crude protein (CP), phosphorus, and calcium (Dairy One, Ithaca, NY). Gross energy (GE) content was assessed at Auburn University using an adiabatic oxygen bomb calorimeter (Parr 6300 bomb calorimeter; Parr Instruments Co., Moline, IL.).

Determination of TiO_2 concentration present in the digesta samples used a modified Short et al. (1996) procedure. Each freeze-dried digesta sample was ashed and dissolved in sulfuric acid. Addition of hydrogen peroxide produced an orange color, with color intensity correlating to titanium dioxide concentration. Replicate aliquots of the resulting solution were analyzed with a UV spectrophotometer (SpectraMax Plus^{384} Absorbance Microplate Reader, Molecular Devices, LLC., San Jose, CA) and absorbance was measured at 410 nm.

Apparent ileal digestibility (AID) of GE, fat, CP, phosphorus, and calcium were calculated using the following equation from Stein et al. (2007):

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

where (Nutrient / TiO_2) = ratio of CP, fat, GE, phosphorus, or calcium to TiO_2 in the diet or ileal digesta. Apparent ileal digestible energy (AIDE) was calculated by multiplying GE digestibility (%) values by feed GE content (Gautier and Rochell, 2020).

Corn Particle Size Determination

Corn particle size in each diet formulation was determined by the ANSI/ASAE S319.4 procedure. Thirteen sieves were used, and each was weighed with a bottom collection pan to measure empty weight. Sieves were stacked in descending order based on the diameter of the opening. One hundred grams of test sample were placed on the top sieve, then the stack was covered and shaken for 10 minutes by an Advantech™ DuraTap shaker (Advantech Manufacturing, Inc., New Berlin, WI). Sieves were weighed separately to collect the weight of the remaining samples, which were entered into a spreadsheet with the standard method formulas:

$$\text{GMD} = \text{dgw} = \log \frac{\sum (wi\ X\ logdi)}{\sum wi}$$

$$\text{SGW} = \text{Sgw} = \log \left(\frac{\sum wi\ \ x\ \ (\log di - logdgw)2}{\sum wi} \right) 0.5$$

$$\text{SA} = \frac{\beta s^{wi}}{\beta v^{Pd}{}_{aw}} \exp\ [0.5[ln\ \sigma]^2]$$

$$\text{PPG} = \frac{wi}{\beta v^{Pd}{}_{aw^3}} \exp\ [4.5[ln\ \sigma]^2]$$

d = diameter, µm

wi = weight of remaining sample on sieve, g

ɲd = d of sieve above weighed

Rd = d of weighed sieve

Logd$_{i\ =\ 0.5}$ x log (αd x βd)

SA = surface area, cm^2

PPG = particles per g

β_s = shape factor for calculating surface area of particles (cubical, β_s = 6; spherical, $\beta_s = \pi$)

β_v = shape factor for calculating surface area of particles (cubical, β_s = 1; spherical, β_s = $\pi/6$)

p = particle density of material (g/cm^3)

$ln\ \sigma$ = standard deviation of log – normal distribution, cm

Statistical Analysis

Data were analyzed as a completely randomized design with battery cage as the experimental unit. Each treatment contained 6 replicate cages. Treatment main effect significance for performance, organ weights, and nutrient digestibility were determined using the GLM procedure of the SAS statistical package (SAS, 2017), with data analyzed as a one-way ANOVA. The following model was used:

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

where Y_{ij} is the observed response of broilers per cage; μ is the overall mean; T_i is the fixed effect of corn particle size treatment; $ß_j$ is the effect of the *j*th block; and ε_{ij} is the residual error when cage was regarded as an experimental unit, $\varepsilon_{ij}\ N\ (0, \sigma\varepsilon^{2})$. Mean values among the 3 corn particle size treatments were separated using Tukey's HSD procedure. Statistical significance was established at $P \leq 0.05$, and tendencies were considered at $0.10 > P > 0.05$.

CHAPTER IV

RESULTS AND DISCUSSION

Performance

The influence of dietary particle size on BW, FC, and FCR for trials 1 and 2 is shown in Tables 3 and 4, respectively. Overall, there were no significant treatment effects in trial 1 for BW on d 7, 14, or 21 or d 1 to 7, 1 to 14, and 1 to 21 FC. There were treatment effects for FCR between d 1 to 7, with birds on the 2036 μm CPS treatment having an elevated FCR (0.86 g:g) compared to birds on the 832 μm (0.82 g:g) treatment. Treatment differences only approached significance for d 1 to 14 (*P=0.055*) and d 1 to 21 (*P=0.052*) FCR, with the highest FCR for both periods associated with the 2036 μm CPS. In trial 2, there were treatment effects observed for BW at d 7, with BW increasing as CPS decreased. Body weight differences at d 14 approached significance (*P=0.080*), with BW increasing as CPS decreased (Table 4). There were no treatment differences identified for BW at d 21, or d 1 to 7, 1 to 14, and 1 to 21 FC. There were no significant treatment effects for FCR in trial 2.

Agreeing with the results from trial 1, Rubio et al. (2020) showed no CPS effects on weight gain during the starter and grower periods. Jacobs et al. (2010) reported BW was not influenced by corn particle sizes of 557, 858, 1210, or 1387 μm during either the d 0 to 7 or d 0 to 21 feeding periods. Parsons et al. (2006) found FCR to increase as dietary CPS increased during the 21 to 42-day period. Similarly, Rubio et al. (2020) observed CPS did not affect feed consumption or FCR during d 1 to 14. Agreeing with the results from both trials, Jacobs et al. (2010) noted that FC was not influenced by corn particle size in any trial. Amerah et al. (2008), however, showed a pattern for FC to decrease, BW gain to increase, and FCR to improve with coarse grinding of corn. Singh et al. (2014) detected increases in FC and weight gain associated with increasing inclusion of coarse CPS in mash diets, whereas the present study (both trials) observed no CPS effect on FC. An opposing relationship between BW and particle size was detected in trial 2. Consideration should be given to the physical feed form when evaluating the effects of particle size. Corn particle size influences appear greater in mash diets, compared to pelleted or crumbled feeds (Singh et al., 2014). Differences between the results of the current study using crumbled feed and those in literature may be owed to feed form.

Organ Measurements

There were no treatment effects on crop or gizzard weights in trial 1 (Table 5) or trial 2 (Table 6), nor trial 1 ceca weights (absolute weight and g/kg of BW, $P>0.05$) (Table 5). Trial 1 proventriculus absolute weights approached significance between treatments ($P=0.064$), with the largest proventriculus weight reported in birds consuming the smallest CPS. This tendency did not translate to relative (g/kg of BW) proventriculus weights ($P=0.206$). Significant treatment effects were reported for trial 2 proventriculus absolute and relative weights, with the largest weights corresponding to birds fed the smallest CPS diets (Table 6).

Corn particle size effects have been observed on relative gizzard weights, with the greatest values corresponding to birds on the largest CPS diets (Parsons et al., 2006; Amerah et al., 2008; Singh et al., 2014; Jacobs et al., 2010). The proventriculus data agrees with the study conducted by Xu et al. (2017), reporting an inclusion of coarse (1145 µm) CPS led to decreased absolute and relative proventriculus weights at 49 d. Ceca absolute weights approached significance among treatments in trial 2 ($P=0.076$), with birds consuming the largest CPS having the smallest ceca weight. This tendency was not present in relative (g/kg of BW) ceca weights.

Nutrient Digestibility

There were no treatment effects for AIDE or CP, fat, and phosphorus digestibility for either trial (Table 7 and 8). In both experiments, treatment influences for calcium digestibility were observed, with digestibility reduced for birds consuming the smallest CPS. Xu et al. (2015) observed 25 and 50% inclusion of coarsely ground (1,362 μm) corn in crumbled broiler diets increased AIDE compared to diets without coarse corn, whereas the present study observed no CPS impact on AIDE. These results agree with Mtei et al. (2019), observing no CPS treatment effects on crude protein or fat digestibility. Diets with coarse (912μm) and medium-ground (700μm) corn led to increased calcium digestibility when compared to finely ground diets but had no effect on phosphorus digestion (Mtei et al., 2019). The increase in calcium digestibility could be attributed to greater retention time in the GI tract resulting from coarse CPS, improving mineral availability (Amerah et al., 2008; Mtei et al., 2019).

CHAPTER V

CONCLUSION AND APPLICATION

Evaluation of varying corn particle sizes (832, 1432, and 2036 μm) in broiler diets during the early grow-out phase showed minimal influence on performance, organ weights, and nutrient digestibility. There is some indication that increasing CPS can negatively affect early FCR, smaller CPS can increase early BW, and smaller CPS may be associated with an enlarged proventriculus. Corn particle size influenced proventriculus absolute and relative weights, with the largest weights corresponding to birds on the smallest CPS diets. Both trials demonstrated treatment differences for calcium digestibility. In addition to long term impacts of corn particle size on broiler development, further research is warranted to assess the role feed form plays in CPS influences on broiler performance and organ parameters. Overall, the results of this study indicate that coarsely ground corn particles may be included in broiler starter diets with limited adverse effects. Inclusion of larger corn particles may decrease energy consumption during milling and overall production costs.

TABLES

Table 2. Ingredient and nutrient composition of broiler starter diet (Trial 1 and 2).

Ingredient, % as fed	**Composition**
Corn	49.4
Conventional Soybean Meal	38.4
Corn Oil	4.1
Distillers Dried Grains with Solubles (DDGS)	4.0
Dicalcium phosphate	1.63
Ground Limestone	1.63
Salt (NaCl)	0.38
Methionine 99%	0.33
Lysine	0.17
Mineral Premix[A]	0.10
Vitamin Premix[B]	0.10
Choline	0.07
Calculated Analysis	
Metabolizable Energy, kcal/kg	3,000
Crude Protein, %	23.2
Calcium, %	1.0
Available phosphorus, %	0.4
Sodium, %	0.2
Potassium, %	1.0
Zinc, ppm	133.7
Selenium, ppm	0.4
Vitamin A, IU/kg	18,739
Vitamin D_3, ICU/kg	6,614
Vitamin E, IU/Kg	78.2
Thiamin, ppm	8.3
Riboflavin, ppm	23.9
Niacin, ppm	107.5
Choline, ppm	1,700
Magnesium, ppm	541.8
Chlorine, %	0.30
Digestible Lys, %	1.23
Digestible Met, %	0.64

Digestible Thr, %	0.73
Digestible Trp, %	0.25
Digestible Arg, %	1.40

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

[B] Vitamin premix included per kg of diet: Vitamin A (Vitamin A acetate), 18,739 IU; Vitamin D (cholecalciferol), 6614 IU; Vitamin E (DL-alpha tocopherol acetate), 66 IU; menadione (menadione sodium bisulfate complex), 4 mg; Vitamin B12 (cyanocobalamin), 0.03 mg; folacin (folic acid), 2.6 mg; D-pantothenic acid (calcium pantothenate), 31 mg; riboflavin (riboflavin), 22 mg; niacin (niacinamide), 88 mg; thiamine (thiamine mononitrate), 5.5 mg; D-biotin (biotin), 0.18 mg; and pyridoxine (pyridoxine hydrochloride), 7.7 mg.

Table 3. Influence on live performance of varying corn particle size from 832 to 2,036 μm in a broiler starter diet fed from 1 to 21 days (least squares means) (Trial 1).

	Corn particle size (μm)[A]				
Item	832	1,432	2,036	$P_r > F$	SEM
Average body weight, g/bird					
Day 1	44.7	44.4	44.4	0.750	0.28
Day 7	194	192	193	0.918	2.2
Day 14	515	516	521	0.670	4.8
Day 21	1,021	1,020	1,011	0.722	9.8
Cumulative feed consumption, g/bird					
Day 1 to 7	160	165	180	0.185	7.3
Day 1 to 14	584	579	609	0.155	11.1
Day 1 to 21	1,277	1,251	1,275	0.463	16.2
Adjusted feed conversion[B], g:g					
Day 1 to 7	0.82[a]	0.85[ab]	0.86[b]	0.019	0.009
Day 1 to 14	1.11	1.11	1.15	0.055	0.012
Day 1 to 21	1.23	1.23	1.25	0.052	0.007

[A] Determined by ASABE 319.4 (13 sieve) method.
[B] Adjusted for mortality.
[ab] Means in the same row with different superscript letters are significantly different (*P* < 0.05).

Table 4. Influence on live performance of varying corn particle size from 832 to 2,036 μm in a broiler starter diet fed from 1 to 21 days (least squares means) (Trial 2).

	Corn particle size (μm)[A]				
Item	832	1,432	2,036	$P_r > F$	SEM
Average body weight, g/bird					
Day 1	41.0	40.9	40.9	0.826	0.17
Day 7	180[a]	176[ab]	169[b]	0.050	3.0
Day 14	500	500	474	0.080	8.7
Day 21	1,020	1,031	1,002	0.446	16.2
Cumulative feed consumption, g/bird					
Day 1 to 7	178	167	163	0.429	8.4
Day 1 to 14	635	621	611	0.511	14.6
Day 1 to 21	1,411	1,407	1,423	0.939	32.3
Adjusted feed conversion[B], g:g					
Day 1 to 7	0.96	0.93	0.95	0.832	0.040
Day 1 to 14	1.22	1.22	1.25	0.252	0.015
Day 1 to 21	1.36	1.35	1.39	0.189	0.017

[A] Determined by ASABE 319.4 (13 sieve) method.
[B] Adjusted for mortality.
[ab] Means in the same row with different superscript letters are significantly different ($P < 0.05$)

Table 5. Influence on organ weights of varying corn particle size from 832 to 2,036 µm in a broiler starter diet fed from 1 to 21 days (least squares means) (Trial 1).

	Corn particle size (µm)[A]				
Item	832	1,432	2,036	$P_r > F$	SEM
Crop					
g/bird	3.46	3.44	3.56	0.800	0.132
g/kg body weight	3.39	3.48	3.53	0.802	0.149
Proventriculus					
g/bird	6.65	5.93	5.92	0.064	0.230
g/kg body weight	6.52	6.01	5.87	0.206	0.259
Gizzard					
g/bird	14.86	15.33	15.31	0.726	0.460
g/kg body weight	14.57	15.48	15.16	0.422	0.480
Ceca					
g/bird	3.99	3.76	3.65	0.317	0.154
g/kg body weight	3.91	3.79	3.62	0.413	0.148

[A] Determined by ASABE 319.4 (13 sieve) method.

Table 6. Influence on organ weights of varying corn particle size from 832 to 2036 μm in a broiler starter diet fed from 1 to 21 days (least squares means) (Trial 2).

	Corn particle size (μm)[A]				
Item	832	1,432	2,036	$P_r > F$	SEM
Crop					
g/bird	3.66	3.52	3.33	0.440	0.178
g/kg body weight	3.72	3.41	3.32	0.332	0.188
Proventriculus					
g/bird	7.20[a]	6.22[b]	6.12[b]	0.001	0.178
g/kg body weight	7.08[a]	6.03[b]	6.13[b]	0.010	0.230
Gizzard					
g/bird	14.26	15.15	14.43	0.172	0.335
g/kg body weight	14.01	14.70	14.40	0.431	0.364
Ceca					
g/bird	3.83	4.03	3.68	0.076	0.098
g/kg body weight	3.90	3.80	3.68	0.689	0.175

[A] Determined by ASABE 319.4 (13 sieve) method.
[ab] Means in the same row with different superscript letters are significantly different ($P < 0.05$).

Table 7. Influence of varying corn particle size from 832 to 2,036 µm on apparent ileal digestible energy (AIDE) and ileal digestibility of crude protein (CP), fat, calcium (Ca) and phosphorus (P) (Trial 1).

	Corn particle size (µm)[A]				
Item	832	1,432	2,036	$P_r > F$	SEM
Digestibility, %					
Crude protein	57.57	54.61	53.42	0.294	1.854
Fat	74.10	73.19	70.67	0.261	1.467
Calcium	44.28[b]	53.18[a]	55.76[a]	0.001	1.817
Phosphorus	42.65	41.30	44.86	0.453	1.966
Apparent ileal digestible energy, kcal/kg	2,609	2,535	2,638	0.444	57.2

[A] Determined by ASABE 319.4 (13 sieve) method.
[ab] Means in the same row with different superscript letters are significantly different ($P < 0.05$).

Table 8. Influence of varying corn particle size from 832 to 2,036 µm on apparent ileal digestible energy (AIDE) and ileal digestibility of crude protein (CP), fat, calcium (Ca) and phosphorus (P) (Trial 2).

	Corn particle size (µm)[A]				
Item	832	1,432	2,036	$P_r > F$	SEM
Digestibility, %					
Crude protein	55.51	58.24	56.43	0.162	0.966
Fat	78.29	80.63	79.45	0.449	1.272
Calcium	44.01[b]	59.44[a]	60.42[a]	0.000	2.202
Phosphorus	44.71	48.11	47.75	0.575	2.464
Apparent ileal digestible energy, kcal/kg	2,618	2,627	2,636	0.923	33.0

[A] Determined by ASABE 319.4 (13 sieve) method.
[ab] Means in the same row with different superscript letters are significantly different ($P < 0.05$).

REFERENCES

Abadi, M.H.M.G., H. Moravej, M. Shivazad, M.A.K. Torshizi, and W.K. Kim. 2019. Effects of feed form and particle size, and pellet binder on performance, digestive tract parameters, intestinal morphology, and cecal microflora populations in broilers. Poult. Sci. 98:1432-1440. doi:10.3382/ps/pey488

Abdollahi, M.R., F. Zaefarian, L. Hall, and J.A. Jendza. 2020. Feed acidification and steam-conditioning temperature influence nutrient utilization in broiler chickens fed wheat-based diets. Poult. Sci. 99:5037-5046. doi:10.1016/j.psj.2020.06.056

Amerah, A.M., V. Ravindran, R.G. Lentil, and D.G. Thomas. 2008. Influence of Feed Particle Size on the Performance, Energy Utilization, Digestive Tract Development, and Digesta Parameters of Broiler Starters Fed Wheat- and Corn-Based Diets. Poult. Sci. 87:2320-2328. doi:10.3382/ps.2008-00149

Behnke, K.C. 1996. Feed manufacturing technology: current issues and challenges. Anim. Feed Sci. Tech. 62:49-57. doi:10.1016/S0377-8401(96)01005-X

Berto, D.A., E.A. Garcia, C. Móri, A.B.G. Faitarone, K. Pelícia, and A.B. Molino. 2007. Performance of Japanese Quails Fed Feeds Containing Different Corn and Limestone Particle Sizes. Braz. J. Poult. Sci. 9:167-171. doi:10.1590/S1516-635X2007000300005

Coffey, D., K. Dawson, P. Ferket, and A. Connolly. 2016. Review of the feed industry from a historical perspective and implications for its future. J. Appl. Anim. Nutr. 4:1-11. doi:10.1017/jan.2015.11

Cufadar, Y., O. Olgun, and A.Ö. Yildiz. 2011. The effect of dietary calcium concentration and particle size on performance, eggshell quality, bone mechanical properties and tibia mineral contents in moulted laying hens. Brit. Poult. Sci. 52:761-768. doi:10.1080/00071668.2011.641502

Daniel, C.R., A.J. Cross, C. Koebnick, and R. Sinha. 2011. Trends in meat consumption in the United States. Public Health Nutr. 14:575-583. doi:10.1017/S1368980010002077

Ege, G., M. Bozkurt, B. Koçer, A.E. Tüzün, M. Uygun, and G. Alkan. 2019. Influence of feed particle size and feed form on productive performance, egg quality, gastrointestinal tract traits, digestive enzymes, intestinal morphology, and nutrient digestibility of laying hens reared in enriched cages. Poult. Sci. 98:3787-3801. doi:10.3382/ps/pez082

FAO: Food and Agriculture Organization of the United Nations. 2022. Crops and livestock products. February 20, 2022. https://www.fao.org/faostat/en/#data/QCL

Fu, Z., H. Yang, H. Han, D. Jia, L. Xu, G. Su, and Z. Wang. 2021. Effect of whole-grain rice on pellet quality, geese performance, and economic benefits. J. Appl. Poult. Res. 30:100176. doi:10.1016/j.japr.2021.100176

Gautier, A.E., and S.J. Rochell. 2020. Influence of coccidiosis vaccination on nutrient utilization of corn, soybean meal, and distillers dried grains with solubles in broilers. Poult. Sci. 99:3540–3549. doi:10.1016/j.psj.2020.03.035

Hafeez, A., A. Mader, I. Ruhnke, I. Röhe, F. Goodarzi Boroojeni, M.S. Yousaf, K. Männer, J. Zentek. 2015. Implication of milling methods, thermal treatment, and particle size of feed in layers on mineral digestibility and retention of minerals in egg contents. Poult. Sci. 94:240-248. doi:10.3382/ps/peu070

Hall, L.E., R.B. Shirley, R.I. Bakalli, S.E. Aggrey, G.M. Pesti, and H.M. Edwards. 2003. Power of two methods for the estimation of bone ash of broilers. Pout. Sci. 82:414-418. doi:10.1093/ps/82.3.414

Herrera, J., B. Saldaña, P. Guzmán, L. Cámara, and G.G. Mateos. 2017. Influence of particle size of the main cereal of the diet on egg production, gastrointestinal tract traits, and body measurements of brown laying hens. Poult. Sci. 96:440-448. doi:10.3382/ps/pew256

Huang, D.S., D.F. Li, J.J. Xing, Y.X. Ma, Z.J. Li, and S.Q. Lv. 2006. Effects of Feed Particle Size and Feed Form on Survival of Salmonella typhimurium in the Alimentary Tract and Cecal S. typhimurium Reduction in Growing Broilers. Poult. Sci. 85:831-836. doi:10.1093/ps/85.5.831

Jacob, J. (2022). Corn In Poultry Diets. United States Cooperative Extension System. Accessed Feb. 2022. https://poultry.extension.org/articles/feeds-and-feeding-of-poultry/feed-ingredients-for-poultry/cereals-in-poultry-diets/corn-in-poultry-diets/

Jacobs, C.M., P.L. Utterback, and C.M. Parsons. 2010. Effects of corn particle size on growth performance and nutrient utilization in young chicks. Poult. Sci. 89:539-544. doi:10.3382/ps.2009-00434

Jafarnejad, S., M. Farkhoy, M. Sadegh, and A.R. Bahonar. 2010. Effect of Crumble-Pellet and Mash Diets with Different Levels of Dietary Protein and Energy on the Performance of Broilers at the End of the Third Week. Vet. Med. Int. 2010:328123. doi:10.4061/2010/328123

Kiarie, E. G., and A. Mills. 2019. Role of Feed Processing on Gut Health and Function in Pigs and Poultry: Conundrum of Optimal Particle Size and Hydrothermal Regimens. Front. Vet. Sci. 6:1-13. doi:10.3389/fvets.2019.00019

Koch, K. 2002. Hammermills and Roller Mills. Kansas State University Agricultural Experiment Station and Cooperative Extension Service. MF-2048. https://bookstore.ksre.ksu.edu/pubs/mf2048.pdf

Lichovnikova, M. 2007. The effect of dietary calcium source, concentration and particle size on calcium retention, eggshell quality and overall calcium requirement in laying hens. Brit. Poult. Sci. 48:71-75. doi:10.1080/00071660601148203

Liermann, W., M. Bochnia, A. Berk, V. Böschen, L. Hüther, A. Zeyner, and S. Dänicke. 2019. Effects of Feed Particle Size and Hydro-Thermal Processing Methods on Starch Modification, Nutrient Digestibility and the Performance and the Gastrointestinal Tract of Broilers. Anim. 9:294-314. doi:10.3390/ani9060294

Liu, Y.H., X.S. Piao, D.Y. Ou, Y.H. Cao, D.S. Huang, and D.F. Li. 2006. Effects of Particle Size and Physical Form of Diets on Mast Cell Numbers, Histamine, and Stem Cell Factor Concentration in the Small Intestine of Broiler Chickens. Poult. Sci. 85:2149-2155. doi:10.1093/ps/85.12.2149

Lu, J., X.L. Kong, Z.Y. Wang, H.M. Yang, K.N. Zhang, and J.M. Zou. 2011. Influence of whole corn feeding on the performance, digestive tract development, and nutrient retention of geese. Poult. Sci. 90:587-594. doi:10.3382/ps.2010-01054

Lu, J., Z.Y. Wang, H.M. Yang, J.M. Zou, and K.N. Zang. 2013. Influence of whole corn feeding on the performance, digestive tract development and nutrient retention of geese from 28 to 70 days of age. Arch.Geflügelk. 77:96-101. ISSN 0003-9098.

Lv, M., L. Yan, Z. Wang, S. An, M. Wu, and Z. Lv. 2015. Effects of feed form and feed particle size on growth performance, carcass characteristics and digestive tract development of broilers. Anim. Nutr. 1:252-256. doi:10.1016/j.aninu.2015.06.001

Lyu, F., M. Thomas, W.H. Hendriks, and A.F.B. van der Poel. 2020. Size reduction in feed technology and methods for determining, expressing and predicting particle size: A review. Anim. Feed Sci. Tech. 261:114-347. doi:10.1016/j.anifeedsci.2019.114347

MacIsaac, J.L., and D.M. Anderson. 2007. Effect of whole wheat, enzyme supplementation and grain texture on the production performance of laying hens. Can. J. Anim. Sci. 87: 579–589.

Manangi, M.K., P. Maharjan, and C.N. Coon. 2018. Calcium particle size effects on plasma, excreta, and urinary Ca and P changes in broiler breeder hens. Poult. Sci. 97:2798-2806. doi:10.3382/ps/pey043

Mtei, A.W., M.R. Abdollahi, N.M. Schreurs, and V. Ravindran. 2019. Impact of corn particle size on nutrient digestibility varies depending on bird type. Poult. Sci. 98:5504-5513. doi:10.3382/ps/pez206

Muramatsu, K., A. Massuquetto, F. Dahlke, and A. Maiorka. 2015. Factors that Affect Pellet Quality: A Review. J. Agric. Sci. Technol. 5:717-722. doi:10.17265/2161-6256/2015.09.002

National Chicken Council. 2022. Per Capita Consumption of Poultry and Livestock, 1965 to Forecast 2022, in Pounds. Accessed Feb. 2022. https://www.nationalchickencouncil.org/about-the-industry/statistics/per-capita-consumption-of-poultry-and-livestock-1965-to-estimated-2012-in-pounds/

Naderinejad, S., F. Zaefarian, M.R. Abdollahi, A. Hassanabadi, H. Kermanshahi, and V. Ravindran. 2016. Influence of feed form and particle size on performance, nutrient utilisation, and gastrointestinal tract development and morphometry in broiler starters fed maize-based diets. Anim. Feed. Sci. Tech. 215:92-104. doi:10.1016/j.anifeedsci.2016.02.012

Nir, I., R. Hillel, I. Ptichi, and G. Shefet. 1995. Effect of Particle Size on Performance.: 3. Grinding Pelleting Interactions. Poult. Sci. 74:771-783. doi:10.3382/ps.0740771

Parsons, A.S., N.P. Buchanan, K.P. Blemings, M.E. Wilson, and J.S. Moritz. 2006. Effect of Corn Particle Size and Pellet Texture on Broiler Performance in the Growing Phase. J. Appl. Poult. Res. 15: 245-255. doi:10.1093/japr/15.2.245

Pelicia, K., E. Garcia, C. Móri, A.B.G. Faitarone, A.P. Silva, A.B. Molino, F. Vercese, and D.A. Berto. 2009. Calcium Levels and Limestone Particle Size in the Diet of Commercial Layers at the End of the First Production Cycle. Braz. J. Poult. Sci. 11:87-94. doi:10.1590/S1516-635X2009000200003

Pizzolante, C.C., E.S.P.B. Saldanha, C. Laganá, S.K. Kakimoto, and C.K. Togashi. 2009. Effects of Calcium Levels and Limestone Particle Size on The Egg Quality of Semi-Heavy Layers in Their Second Production Cycle. Braz. J. Poult. Sci. 11:79-86. doi:10.1590/S1516-635X2009000200002

Rubio, A.A., J.B. Hess, W.D. Berry, W.A. Dozier, and W.J. Pacheco. 2020. Effects of corn particle size on broiler performance during the starter, grower, and finisher periods. J. Appl. Poult. Res. 29:352-361. doi:10.1016/j.japr.2019.11.009

Ruhnke, I., I. Röhe, C. Krämer, F.G. Boroojeni, F. Knorr, A. Mader, E. Schulze, A. Hafeez, K. Neumann, R. Löwe, and J. Zentek. 2015. The effects of particle size, milling method, and thermal treatment of feed on performance, apparent ileal digestibility, and pH of the digesta in laying hens. Poult. Sci. 94: 692-699. doi:10.3382/ps/pev030

Safaa, H.M., E. Jiménez-Moreno, D.G. Valencia, M. Frikha, M.P. Serrano, and G.G. Mateos. 2009. Effect of main cereal of the diet and particle size of the cereal on productive performance and egg quality of brown egg-laying hens in the early phase of production. Poult. Sci. 88:608-614. doi:10.3382/ps.2008-00328

Saki, A., A. Rahmani, and A. Yousefi. 2019. Calcium particle size and feeding time influence egg shell quality in laying hens. Acta Sci., Anim. Sci. 41:1-7. doi:10.4025/actascianimsci.v41i1.42926

SAS Institute. 2017. SAS/STAT® User's Guide Version 14.3; SAS Institute, Inc.: Cary, NC, USA; Available online:https://support.sas.com/documentation/onlinedoc/stat/143/hpreg.pdf (accessed on 1 June 2021).

Saunders-Blades, J.L., J.L. MacIsaac, D.R. Korver, and D.M. Anderson. 2009. The effect of calcium source and particle size on the production performance and bone quality of laying hens. Poult. Sci. 88:338-353. doi:10.3382/ps.2008-00278

Shen, T. F., and W. L. Chen. 2003. The Role of Magnesium and Calcium in Eggshell Formation in Tsaiya Ducks and Leghorn Hens. Asian-Aust. J. Anim. Sci. 16:290-296. doi:10.5713/ajas.2003.290

Short, F.J., P. Gorton, J. Wiseman, and K.N. Boorman. 1996. Determination of titanium dioxide added as an inert marker in chicken digestibility studies. Anim. Feed Sci. Tech. 59:215-221. doi:10.1016/0377-8401(95)00916-7

Singh, Y., V. Ravindran, T.J. Wester, A.L. Molan, and G. Ravindran. 2014. Influence of feeding coarse corn on performance, nutrient utilization, digestive tract measurements, carcass characteristics, and cecal microflora counts of broilers. Poult. Sci. 93:607-616. doi:10.3382/ps.2013-03542

Svihus, B. 2006. The role of feed processing on gastrointestinal function and health in poultry. In: G.C. Perry, editor, Avian Gut Function in Health and Disease. p. 183-194.

Svihus, B. 2014. Function of the digestive system. J. Appl. Poult. Res. 23:306-314. doi:10.3382/japr.2014-00937

Teixeira Netto, M.V., A. Massuquetto, E.L. Krabbe, D. Surek, S.G. Oliveira, and A. Maiorka. 2019. Effect of Conditioning Temperature on Pellet Quality, Diet Digestibility, and Broiler Performance. J. Appl. Poult. Res. 28:963-973. doi:10.3382/japr/pfz056

USDA. 2021. Feedgrains Sector at a Glance. Accessed Feb. 2022. https://www.ers.usda.gov/topics/crops/corn-and-other-feedgrains/feedgrains-sector-at-a-glance/

van der Poel, A.F.B., M.R. Abdollahi, H. Cheng, H. Colovic, L.A. den Hartog, D. Miladinovic, G. Page, K. Sijssens, J.F. Smillie, M. Thomas, W. Wang, P. Yu, and W.H. Hendricks. 2020. Future directions of animal feed technology research to meet the challenges of a changing world. Anim. Feed Sci. Tech. 270:114-692. doi:10.1016/j.anifeedsci.2020.114692

van Soest, P.J., and V.C. Mason. 1991. The influence of the Maillard reaction upon the nutritive value of fibrous feeds. Anim. Feed Sci. Tech. 32:45-53. doi:10.1016/0377-8401(91)90008-G

Wang, Z.Y., H.M. Yang, J. Lu, W.Z. Li, and J.M. Zou. 2014. Influence of whole hulled rice and rice husk feeding on the performance, carcass yield and digestive tract development of geese. Anim. Feed Sci. Tech. 194:99-105. doi:10.1016/j.anifeedsci.2014.04.009

Xu, Y., M. Lin, C.R. Stark, P.R. Ferket, C.M. Williams, and J. Brake. 2017. Effects of dietary coarsely ground corn and 3 bedding floor types on broiler live performance, litter characteristics, gizzard and proventriculus weight, and nutrient digestibility. Poult. Sci. 96:2110–2119. doi:10.3382/ps/pew485

Xu, Y., C.R. Stark, P.R. Ferket, C.M. Williams, W.J. Pacheco, and J. Brake. 2015. Effect of dietary coarsely ground corn on broiler live performance, gastrointestinal tract development, apparent ileal digestibility of energy and nitrogen, and digesta particle size distribution and retention time. Poult. Sci. 94: 53-60. doi:10.3382/ps/peu015

Zaefarian, F., M.R. Abdollahi, and V. Ravindran. 2016. Particle size and feed form in broiler diets: impact on gastrointestinal tract development and gut health. World's Poult. Sci. J. 72:277-290. doi:10.1017/S0043933916000222

GLOSSARY

Apparent ileal digestible energy	A measure of available energy in feed that reflects digestibility at the ileal level in the small intestine.
Bifidobacteria	A genus of anaerobic, probiotic bacteria part of the normal microflora in the gastrointestinal tract.
Broilers	Chickens that are bred and raised for meat production.
Broiler breeders	Chickens raised as parent stock to produce the broilers.
Ceca	Two pouches located at the junction of the small and large intestines for fermentation, mineral absorption, and water absorption.
Clostridium	A genus of pathogenic Gram-positive bacteria.
Crop	A thin-walled pouch part of a bird’s digestive tract for storing food before digestion.
Crude protein (CP)	A measurement of the total nitrogen content in feed, including non-protein and true protein nitrogen.
Crystallinity	The structural order in a solid based on the regular arrangement of atoms.
Cumulative Feed Consumption (FC)	The total amount of feed consumed by a bird over a specified period.
Digesta	Feed or forage undergoing digestion.
Endogenous enzyme	Enzymes produced by the animal’s body.
Exogenous enzyme	Enzymes not produced by the animal and are added to feed to target components of the diet.
Feed conversion ratio (FCR)	A ratio measuring the efficiency with which livestock convert animal feed into the desired output.
Gizzard	A muscular, thick-walled part of a bird's digestive tract for grinding food.

Hydrothermal processing	A treatment of animal feed using mechanical compression in combination with moisture, heat, steam pressure, and shear forces to aggregate small particles into larger ones.
Ileo-colonic-cecal junction	A point along the course of the gastrointestinal tract where the small intestine (ileum) terminates at the openings to the ceca and the large intestine.
Ileum	The last section of the small intestine.
Lactobacilli	A genus of anaerobic, probiotic bacteria part of the normal microflora in the gastrointestinal tract.
Lyophilized	A low-temperature dehydration process (Freeze drying).
Maillard reaction	A chemical reaction between amino acids and reducing sugars.
Mechanoreceptor	Sensory receptor that responds to mechanical stimuli, such as touch, pressure, vibration, and sound.
Meckel's diverticulum	A small residual sac formed during embryonic development that marks the end of the jejunum (middle part of the small intestine) and the start of the ileum.
Metabolizable energy (AME)	Measurement of the net energy from a feedstuff remaining after fecal and urinary energy loss.
Pendulous crop	An abnormal crop that is greatly dilated and becomes blocked so feed cannot move to the next part of the digestive system.
Phytase	An exogenous enzyme that catalyzes the release of a bioavailable form of phosphorus from phytate.
Proteases	An enzyme that catalyzes proteolysis, breaking down proteins.
Proventriculus	The glandular or true stomach of a bird.
Reverse peristalsis	Gastric reflux transferring the digesta from gizzard to proventriculus via gastro-duodenal contractions.
UV spectrophotometer	An instrument that measures the intensity of light transmitted through a sample used during the analytical technique of UV spectroscopy.

APPENDIX

APPENDIX A

IACUC

INSTITUTIONAL ANIMAL CARE and USE COMMITEE
Office of Research Compliance,
010A Sam Ingram Building,
2269 Middle Tennessee Blvd
Murfreesboro, TN 37129

MIDDLE TENNESSEE STATE UNIVERSITY

IACUCN001: PROTOCOL APPROVAL NOTICE

Friday, October 02, 2020

Senior Investigator	**Kevin Downs** (ROLE: Principal Investigator)
Co-Investigators	NONE
Investigator Email(s)	*kevin.downs@mtsu.edu*
Department	Agriculture
Protocol Title	***Supplementation and feeding strategies for broiler chickens***
Protocol ID	**21-2001**

Dear Investigator(s),

The MTSU Institutional Animal Care and Use Committee has reviewed the animal use proposal identified above under the ***Designated Member Review (DMR) mechanism*** and has approved your protocol in accordance with PHS policy. A summary of the IACUC action(s) and other particulars of this this protocol is tabulated as below:

IACUC Action	**APPROVED for one year**		
Date of Expiration	**9/30/2021**	Approval Date:: 10/2/2020	
Number of Animals	One thousand five hundered and thirty six (1,536)		
Approved Species	**Gallus gallus domesticus (Broiler chickens from Cobb Vantress Hatchery, Lafayette, TN)**		
Category Subclassifications	☐ **Teaching**	☒ **Research**	
	☐ Classroom	☐ Laboratory ☒ Field Research	☐ Field Study
	☐ Laboratory	☒ Handling/Manipulation	☐ Observation
	Comment: NONE		
Approved Site(s)	MTSU Experimental Learning and Research Center, 3211 Guy James Rd, Lascassas, TN 37085		
Restrictions	**1. Satisfy DMR requirements AND annual continuing review.** **2. Follow CDC guidelines and MTSU requirements to counter COVID-19 infection**		
Comments	Approved during COVID-19 emergency		

This approval is effective for three (3) years from the date of this notice (9/30/2023). This protocol **expires on 9/30/2021** The investigator(s) MUST file a Progress Report annually regarding the status of this study. Refer to the schedule for Continuing Review shown below; NO REMINDERS WILL BE SENT. A continuation request (progress report) must be approved

IACUCN001 Version 1.3 Revision Date 04.15.2016 by the IACUC prior to 7/31/2021 for this protocol to be active for its full term. Once a protocol has expired, it cannot be continued and the investigators must request a fresh protocol.

Continuing Review Schedule: Refer tp the following table to request your CR:

Reporting Period	Requisition Deadline	IACUC Comments
First year report	8/31/2021	TO BE COMPLETED
Second year report	8/31/2022	TO BE COMPLETED
Final report	8/31/2023	TO BE COMPLETED

MTSU Policy defines an investigator as someone who has contact with live or dead animals for research or teaching purposes. Anyone meeting this definition must be listed on your protocol and must complete appropriate training through the CITI program. Addition of investigators requires submission of an Addendum request to the Office of Research Compliance.

The IACUC must be notified of any proposed protocol changes prior to their implementation. Unanticipated harms to subjects or adverse events must be reported within 48 hours to the Office of Compliance at (615) 494-8918 and by email – compliance@mtsu.edu.

Post-approval Protocol Amendments:

Date	***Amendment(s)***	***IRB Comments***
NONE	NONE	NONE

All records pertaining to the animal care be retained by the MTSU faculty in charge for at least three (3) years AFTER the study is completed. Be advised that all IACUC approved protocols are subject to audit at any time and all animal facilities are subject to inspections at least biannually. Furthermore, IACUC reserves the right to change, revoke or modify this approval without prior notice.

Sincerely,

Compliance Office
(On behalf of IACUC)
Middle Tennessee State University
Tel: 615 494 8918
Email: iacuc_information@mtsu.edu (for questions) and
lacuc_submissions@mtsu.edu (for sending documents)