Effect of feeding diets with varying energy levels and conditioning temperatures on broiler performance, processing yield, and nutrient digestibility

by

Jose Rodrigo Hernandez Garcia

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Wilmer J. Pacheco, Chair, Associate Professor and Extension Specialist of Poultry Science
Samuel Rochell, Associate Professor of Poultry Science
Ruediger Hauck, Associate Professor of Pathobiology and Poultry Science

ABSTRACT

Pelleting is the most common thermal processing method used in the manufacturing of broiler diets. It is a process that involves the use of heat, moisture, and pressure to agglomerate smaller feed particles into pellets. Previous research has demonstrated the benefits of pelleting, including increased feed intake (**FI**), reduced feed wastage (**FW**) and nutrient segregation, and increased digestibility of some dietary components. Therefore, pellets are the preferred feed form in the US broiler industry. However, there are many factors that may influence the response of birds fed pelleted diets, including conditioning temperatures and the level of metabolizable energy (**ME**) in the diet. For this reason, two trials were designed to evaluate the relationships between feed processing variables and the nutritional value of feed. The objective of the first experiment was to evaluate the main effects and interactions of two ME levels and three conditioning temperatures on broiler performance, processing yield, footpad lesions, tibia ash, and nutrient digestibility from 1 to 42 d of age. A total of 1,350 d-old YPM x Ross 708 male broilers were randomly distributed in 54 floor pens and assigned to six treatments (9 replicates/treatment). Diets were formulated to contain two ME levels (standard energy (**SE**) and -130 kcal/kg reduced energy (**RE**)) in all feeding phases. Basal diets for each ME level were manufactured using three conditioning temperatures (80, 84, and 88°C). Feed intake, body weight (**BW**), and feed conversion ratio (**FCR**) were determined at 14, 28, 35, and 42 d of age. On d 42, ileal digesta (5 birds/pen) was collected for nutrient digestibility analysis and broilers were processed on d 43. Broilers fed SE had improved FCR ($P < 0.05$) compared to broilers fed RE in every evaluated period. Performance parameters from 15-42 d and processing yields were unaffected ($P > 0.05$) by conditioning temperatures. Apparent ileal digestibility (**AID**) of fat and energy was higher ($P < 0.05$) in broilers fed SE compared to broilers fed RE. Broilers fed diets conditioned to 88°C had lower ($P < 0.05$) AID of Ca and P compared to broilers fed diets conditioned to 80 and 84°C. A second study was conducted to evaluate the main effects and interactions of two ME levels and three feed forms on broiler performance, FW, and nutrient digestibility from 1 to 21 d of age. A total of 648 YPM x Ross 708 male broilers were randomly distributed in 72 battery cages (9 birds/cage) and assigned to six treatments (12 replicates/treatment). Starter diets were formulated to contain two ME levels (2,979 [**E2979**] and 2,875 kcal/kg [**E2875**]). Both diets were fed as mash, crumbles conditioned at 85°C, and crumbles conditioned at 90°C. Body weight gain (**BWG**) and FI were determined at 10 and 21 d of age and FCR was adjusted for mortality. On d 10, 15, and 18, the feed spilled was collected from trays placed under each battery cage to calculate FW as g/kg. Ileal digesta (7 birds/cage) was collected for nutrient digestibility analysis on d 21. Broilers fed E2979 diets had lower ($P < 0.05$) FCR (1.28 vs. 1.36 g:g) from 1-21 d compared to broilers fed E2875 diets. Additionally, broilers fed mash diets had lower ($P < 0.05$) FI (1049 vs. 1223 and 1215 g) and higher ($P < 0.05$) FCR (1.34 vs. 1.30 and 1.32 g:g) and FW (28.6 vs. 2.3 and 3.0 g/kg) from 1-21 d compared to broilers fed crumbles conditioned to either 85 or 90°C. The lowest ($P < 0.05$) apparent ileal digestibility AID of dry matter (**DM**) was observed in broilers fed mash diets with E2875. Broilers fed E2979 diets had improved ($P < 0.05$) AID of crude protein (**CP**) compared to broilers fed E2875 diets. Starch digestibility was lower ($P < 0.05$) in broilers fed crumbles conditioned to 90°C compared to broilers fed crumbles conditioned to 85°C and mash. Overall, these studies suggest that broiler performance and nutrient digestibility are influenced by different feed processing parameters as well as by the nutritional value of feed. The obtained results highlight the importance of understanding that the response of birds to diet formulation and processing variables is closely related. Therefore, this relationship should be considered to make decisions that improve broiler performance and nutrient utilization.

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I. INTRODUCTION

Broiler production in the U.S. has steadily increased over the last 12 years and it is expected to continue growing in coming years (USDA, 2023). The greatest expense in poultry production is feed, which represents up to 70% of the total production cost (Ravindran, 2013). Ingredients, particularly energy and protein contributing feedstuffs, make up the greatest proportion of the cost, while feed processing accounts for approximately 5% of the total diet cost (Paulk et al., 2023). Of all the cost centers in a feed manufacturing facility, pelleting consumes the most energy. This process uses mechanical pressure, moisture, and heat to agglomerate smaller feed particles into pellets (Abdollahi et al., 2013a). In this regard, the benefits of pelleting have been well documented in previous literature and include increased feed intake (**FI**) (Engberg et al., 2002; Svihus et al., 2004), reduced selective feeding and nutrient segregation (Forbes and Covasa, 1995), reduced eating time and increased resting frequency (Jensen et al., 1962; Skinner-Noble et al., 2005), and increased digestibility of some dietary components (Abdollahi et al., 2013a). However, pelleting is an expensive process, and several factors need to be considered to maximize the benefits of feeding pelleted diets.

Some of the factors that influence the response of birds to pelleted diets are feed processing variables and the nutritional characteristics of feed. For example, the conditioning temperatures used in the pelleting process may influence some physical and chemical properties of feed. This temperature is regulated through the incorporation of steam into the conditioner (Thomas et al., 1997) and the addition of heat and moisture may result in protein denaturation (Svihus and Zimonja, 2011) and starch gelatinization (Zimonja and Svihus, 2009). The degree of these changes may lead to positive effects such as increased pellet quality, which could improve broiler performance (Abdollahi et al., 2011; Teixeira Netto et al., 2019). However, using high conditioning temperatures may damage some heat labile nutrients, particularly vitamins (Marchetti et al., 1999) and amino acids (Loar II et al., 2014) and reduce the activity of exogenous enzymes (Cowieson et al., 2005; Boltz et al., 2020). According to Abdollahi et al. (2011), the magnitude of the differences observed in broiler performance with varying conditioning temperatures is determined by the balance between negative effects of high conditioning temperatures on nutrient availability and positive effects on pellet quality.

In addition, previous research indicates that broiler response to pelleted diets may be influenced by nutrient density in the diet, particularly amino acids (Rubio et al., 2020) and metabolizable energy (**ME**) (Abdollahi et al., 2018; Massuquetto et al., 2020). Abdollahi et al. (2018) reported that the benefits of pelleting were more pronounced at lower nutrient density levels. This is relevant since energy represents the greatest cost during feed formulation of poultry diets (Dozier III et al., 2006; Ravindran, 2013). Therefore, it is important to understand that feed manufacturing parameters and the nutritional properties of feed may interact to influence broiler performance. Evaluating nutritional strategies that target these interrelationships is valuable to improve nutrient utilization in broiler diets and reduce feeding costs.

For this reason, the research project presented herein consisted of two experiments that were designed to evaluate the relationships between feed processing variables and the nutritional value of feed. Experiment 1 evaluated diets formulated with two ME levels (standard energy and -130 kcal/kg reduced energy), which were manufactured using three conditioning temperatures: 80, 84, 88°C. During each feeding period, broilers were fed six dietary treatments to evaluate performance, processing yield, footpad lesions, tibia ash, and nutrient digestibility from 1 to 42 d of age. The second experiment followed a similar design to evaluate the main effects and interactions of two ME levels and three feed forms on broiler performance, feed wastage (**FW**), and nutrient digestibility from 1 to 21 d of age. The energy levels of the starter diets were 2,979 and 2,875 kcal/kg and both diets were as mash, crumbles conditioned at 85°C, and crumbles conditioned at 90°C, resulting in six dietary treatments.

II. LITERATURE REVIEW

PELLET MANUFACTURING OVERVIEW

The concept of manufacturing poultry feed in the form of pellets was introduced in the early 1900s (Black et al., 1957). Over the years, the pelleting process has evolved to become a standard feed manufacturing process, driven by advances in the equipment used for pelleting (Castaldo, 2014). Currently, pelleting is the most common thermal processing method used in the manufacturing of broiler diets (Abdollahi et al., 2018). The main objective of pelleting is to agglomerate smaller feed particles using mechanical pressure, moisture, and heat (Abdollahi et al., 2013a).

Each step of the pelleting process such as conditioning temperature and retention time during conditioning plays a critical role in the quality of the finished feed. The process and equipment for feed manufacturing may vary between feed mills depending on several factors such as the size of the operation and the intended livestock species for the produced feed. However, feed mills that manufacture broiler feed will follow a similar process, which consists of receiving the ingredients, grinding, batching, mixing, conditioning, pelleting, cooling, and loadout and feed delivery (Amin and Sobhi, 2023).

Generally, the feed manufacturing process starts with receiving the raw materials such as cereal grains, protein sources, crystalline amino acids, vitamins, and mineral premixes among others. Sampling in this stage is crucial to ensure that both ingredients and the finished feed meet quality and nutritional parameters (Glencross et al., 2007). Typically, nutrient analyses are conducted using either wet-chemistry methods or near-infrared reflectance spectroscopy (**NIRS**) to determine the nutritional characteristics of ingredients (Alhotan, 2021). In addition, ingredients can be analyzed for mycotoxin content, antinutritional factors such as trypsin inhibitors, or physical characteristics such as bulk density and particle size (Jones et al., 1995; Pacheco et al., 2013)

Grinding

Most ingredients used in livestock feeds require some type of grinding to make them suitable for feeding and digestion. During grinding, the physical characteristics of ingredients are modified by reducing particle size, which facilitates the subsequent processes of mixing and pelleting (Behnke, 1996). The finer particles produced from the grinding process have a greater surface area for steam penetration and particle binding during conditioning and pelleting, which could yield more durable pellets (Goodband et al., 1995).

The main grinding equipment used in the feed industry are hammermills and roller mills. Hammermills reduce the particle size of ingredients by impact. They use large rotating drums with protruding metal bars (i.e., hammers) that impact the material entering the grinding chamber at high velocity, shattering large particles, and reducing their size (Yancey et al., 2014). In a hammermill, particle size is influenced by several factors including hammer tip speed, hammer pattern, hammer setting, and screen hole diameter (Heiman, 2005). Roller mills reduce particle size by crushing grains through several roller pairs with particle size being primarily determined by the number of roller pairs and the gap between rolls (Dunmire et al., 2021a). The design and operating characteristics of these mills represent certain advantages and disadvantages for the feed industry. For example, roller mills produce a more uniform particle size compared to hammermills (Campbell et al., 2001) and consume less electrical energy (Fang et al., 1997). Reece et al. (1985) reported that a roller mill required 14.5% less energy than a hammermill to grind corn with both mills operating at full motor load. In addition, hammermills are associated with higher dust and noise pollution. Sobczak et al. (2019) observed that hammermills lead to higher dust contamination, producing a higher number of particles under 40, 10, and 1 micron (**µm**) compared to roller mills. However, hammer mills are mostly used in the preparation of broiler feed due to their versatility, ease of operation, and low maintenance (Reece et al., 1985).

The main quality analysis used to assess the grinding process is the particle size analysis. The standard method for evaluating fineness of feed materials is the ASAE method S319.5 (ASABE, 2023). This method consists of agitating and tapping a sample through a set of 13 sieves using a sieve shaker. The sieves have apertures of various sizes, ranging from 4,760 µm to 53 µm. Sieve agitators (i.e., plastic rings or rubber balls) and a dispersion agent can be used to facilitate the sieving of materials prone to agglomeration. After tapping and agitation, the amount of sample retained in each sieve is weighed and used to calculate the geometric mean diameter ($\mathbf{d_{gw}}$) and the geometric standard deviation ($\mathbf{S_{gw}}$) expressed in µm. The uniformity of a particle size distribution in a sample is determined by the S_{gw}. As the S_{gw} increases, the number of large and fine particles increases (Dunmire et al., 2021a). This analysis is particularly important when manufacturing broiler diets, since the particle size of feed ingredients influences pellet quality, broiler performance, gastrointestinal tract development, and nutrient digestibility (Wondra et al., 1995; Amerah et al., 2007; Pacheco et al., 2013; Rubio et al., 2020). Parsons et al. (2006) evaluated five increasing particle sizes of corn (781, 950, 1,042, 1,109, and 2,242 µm) in mash diets and observed that broiler performance decreased when corn particle size exceeded 1,042 µm. In another study by Pacheco et al. (2013), the authors observed that broilers fed diets manufactured using coarse corn (1,330 µm) had 8.5% higher gizzard weights than broilers fed diets manufactured using finely ground corn (520 µm).

Batching and mixing

The objective of the batching process is to weigh each ingredient accurately. Generally, ingredients are classified as major, minor, micro, and liquid depending on their characteristics and inclusion level on the diet. Therefore, equipment used in the batching process should be kept within specification limits to avoid nutritional variation due to over or under addition of ingredients (Stark, 2012). Feed mills typically weigh ingredients using scales with different accuracy and ingredients with small inclusion require greater scale accuracy (Dunmire et al., 2021b).

Mixing is one of the most critical operations in feed manufacturing. Achieving good mixing uniformity not only enhances animal performance, but also ensures regulatory compliance (Behnke, 1996). There is a variety of mixing equipment used in the feed industry including paddle and ribbon mixers (Dunmire et al., 2021b). Generally, mixing consists of a dry cycle and a wet cycle after the addition of liquid ingredients. Mixing time is influenced by several factors such as the surface area of internal mixing parts, ingredient characteristics (i.e., bulk density), and levels of liquid addition. Therefore, mixer performance and mixing times must be evaluated and determined for each mixer type and size (Saensukjaroenphon et al., 2019; Fahrenholz, 2019).

Since broiler feed is fed as a sole source of nutrients, it is critical to evaluate mixing uniformity to ensure that broilers receive all required nutrients in every bite. Mixer uniformity analysis is conducted by testing the concentration of a single-source tracer (e.g., trace minerals, synthetic amino acids, chloride ion from salt, manganese) in a representative set of ten samples (Stark and Saensukjaroenphon, 2017; Fahrenholz, 2019). Samples are analyzed for the concentration of the chosen marker and the results are used to calculate the coefficient of variation (**CV**). According to Herrman and Behnke (1994), a CV below 10% is considered indicative of a good mix, and no corrective actions are necessary. If the obtained CV exceeds 10%, corrective actions should be taken based on the test results. A study by McCoy et al. (1994) emphasized the importance of achieving adequate mixer uniformity in broiler feed. They observed improvements in average daily gain (23.6 vs 30.0 grams), feed conversion ratio (**FCR**) (1.82 vs. 1.72 g:g), and mortality (12 vs. 0%) when mixer uniformity improved and the CV was reduced from 40 to 12%.

Conditioning

After the mixing process, feed can either be bagged or shipped in bulk if intended to be fed as mash or proceed to the pelleting process. The pelleting process is the combination of three different operations: conditioning, pelleting, and cooling. Conditioning is the initial step of the pelleting process, defined as the conversion of a dry mixed mash into a moist and easier to pellet conditioned mash using steam, which provides heat and moisture (Thomas et al., 1997). Mash conditioning is achieved by adding steam into the conditioner, which increases the moisture content and heat of the mash. A proper balance of heat and moisture must be obtained to optimize the conditioning process (Abdollahi et al., 2013a). The increase in moisture and heat depends on the target conditioning temperature, but typically, the moisture content of mash increases around 4% during the conditioning process (Skoch et al., 1981; Thomas and Van der Poel, 2020). A conditioner is essentially a cylinder with an agitator shaft designed to ensure thorough contact and mixing of steam with the mash feed (Behnke and Gilpin, 2014). The main variations of conditioning equipment in the feed industry are single-layer, double-layer, vertical, and retention-conditioner (i.e., hygienizer) (Gilbert and Cooney, 2010; Duan et al., 2017). Conditioners can vary in diameter, length, and speed (Gilbert and Cooney, 2010). The conditioning equipment installed in a feed mill depends on the objectives of the operation. For example, the hygienizer is a jacketed chamber that allows for temperature to be maintained without further injection of direct steam into mash feed (Lynch et al., 2023). Hygienizers are mostly used to increase feed hygienics and as a strategy for *Salmonella* control (Boney et al., 2018; Obe et al., 2023).

During conditioning, the combined effect of moisture and heat significantly alters the physical properties of feed. Steam is homogenously dispersed throughout the mash feed, creating a thin film of water around feed particles, which facilitates binding of feed particles (Thomas et al., 1997). The effect of particle binding is observed due to several reasons, including van der Waals and capillary forces between water molecules (Pileggi et al., 2001). In addition, the presence of heat and water induces a variety of physical and chemical changes on the feed particles. According to Svihus and Zimonja (2011), the temperatures achieved during pelleting may result in protein denaturation and the unfolding of the three-dimensional structure of proteins, which leads to the formation of covalent-bonds such as disulfide bridges and iso-peptide bonds. In addition, there is a degree of starch gelatinization during conditioning as most cereal starches start denaturing at ranges between 50 and 70°C in excess water conditions (Zimonja and Svihus, 2009; Svihus and Zimonja, 2011).

Furthermore, there are several variables that may be manipulated during conditioning, including retention time in the conditioner, conditioning temperature, and steam pressure. Different retention times may be achieved by changing the configuration and angles of the conditioner pick/paddles, adjusting shaft speed with a variable-frequency drive, or using extended-conditioning equipment (Bortone, 2014; Gilpin et al., 2002) such as hygienizers or expanders. Conditioning temperature is modified by controlling the amount of steam entering the conditioner. The amount of heat transfer to the mash feed is defined by the steam enthalpy (Abdollahi et al., 2013a), which is greatly influenced by steam quality (Behnke and Gilpin, 2014). In this regard, steam quality is described by its dryness and is defined by the percentage of steam in the water phase (Campabadal and Maier, 2014; Bortone, 2014). Wet (i.e., unsaturated) steam has substantially lower energy content than dry (i.e., saturated) steam at the same pressure; therefore, the objective of every feed mill is to use the driest steam possible (Behnke and Gilpin, 2014). Additionally, steam pressure is regulated using steam reducing valves before steam enters the conditioner (Campabadal and Maier, 2014). According to Cutlip et al. (2008), the most used values for pressure range from 138 to 552 kPa, while conditioning temperatures range from 77 to 93°C and there must be a proper combination of these variables for an optimum conditioning prior to pelleting.

Pelleting

Pelleting of the conditioned mash is done using a pellet mill. After steam injection in the conditioner, the conditioned mash enters the pelleting chamber, where pellets are formed by compressing and extruding the feed through a metal die using a set of rolls (Abdollahi et al., 2013a; Fairfield, 2014). Depending on the design of the equipment, the pellet chamber may consist of two or three rolls. In most pellet mills, the die revolves around the fixed rolls (Thomas et al., 1997). As feed exits the revolving pellet die, a set of knifes mounted on the inside of the die casting are used to cut the pellet to the desired length (Evans et al., 2019).

Temperature rise during the pelleting process is primarily caused by the addition of steam during conditioning. However, the temperature of the conditioned mash further increases at the mash-die interface as the feed is extruded (Campabadal and Maier, 2014; Tumuluru, 2015). While being forced through the die, the temperature of the feed rises at the pellet surface due to the dissipation of mechanical energy caused by the strong frictional forces between the feed and the surface of the die press channels (Goodarzi Boroojeni et al., 2016). Therefore, the temperature of hot pellets after leaving the die is generally higher in comparison with the temperature of the conditioned mash (Skoch et al., 1981; Thomas and Van der Poel, 1996). The increase in temperature due to frictional heat depends on several factors including diet formulation, conditioning temperature, and die compression ratio, which is the relationship between its effective thickness and the diameter of the die holes. For example, adding more fat in the mixer increases lubrication and reduces frictional heat in the pellet die (Zimonja et al., 2007). Several researchers have reported reductions in motor load with increasing levels of mixer-added fat (Gehring et al., 2011; Loar II et al., 2014; Corey et al., 2014). Skoch et al. (1981) reported that temperature differential between conditioned mash and hot pellets was higher when lower conditioning temperatures were used. Moisture provided by steam addition during conditioning acts as a lubricant in the pellet die. Therefore, feed conditioned at higher temperatures experiences less frictional heat increment during feed extrusion through the pellet die.

Another factor influencing the amount of frictional heat produced during pelleting is the design specifications of the pellet die, including its metallurgy, types of relief, hole inlets and patterns (Turner, 2014). The pellet length-to-diameter ratio (**L/D**) influences pellet quality and production rate. To calculate the L/D ratio, the effective length of the pellet die is divided by its hole diameter. With higher L/D ratios, the forming pellets encounter more shear thus increasing frictional heat as they are extruded through the pellet die (Thomas et al., 1997). According to Campabadal and Maier (2014), thinner dies (i.e., lower L/D ratio) could be used to prevent excessive frictional heating or to increase production rate. However, a higher L/D ratio improves pellet quality. Kaddour (2019) reported an improvement of around 8% in pellet durability when the L/D ratio of the pellet die increased from 7.9 to 13. In addition, other factors such as die speed and gap distance between rolls and pellet die may also influence pellet quality (Thomas et al., 1997; Tabil and Sokhansanj, 1996).

Cooling

Depending on diet formulation, the moisture content of feed entering the conditioner is around 12.5% and pellets exiting the pellet die have a moisture that ranges from 16.0 to 17.5%, representing an increase of around 4 to 5% in the conditioner (Behnke and Gilpin, 2014). The temperature of hot pellets varies depending on the target conditioning temperature and degree of frictional heat increment at the pellet die, but commonly range from 60 to 95°C (Thomas et al., 1997; Cutlip et al., 2008). For feed to be suitable for storage, the temperature must be reduced to about 8°C above the temperature of the ambient air used to cool down the pellets with a moisture content between 10 to 12% (Abdollahi et al., 2013a), depending on the moisture content of the ingredients used in the formulation. Therefore, the objective of cooling is to remove the excess moisture and heat added during conditioning and pelleting.

The mechanism behind the drying and cooling of pellets relies on evaporation of water and convection of heat from pellets to the cooling air (Thomas and Van der Poel, 2020) and to certain extent on heat conduction within the pellet (Lambert et al., 2018). In the feed industry, the main equipment used for cooling are horizontal and counterflow coolers (Thomas et al., 1997). In horizontal conveyor coolers, feed is spread on a belt that moves through the cooler (Rokey et al., 2010). Pre-heated air is circulated through the pellet bed using a cross flow mechanism, with the conveyor belt and air going in opposite directions (Audet, 1995; Salama et al., 2021). In counterflow coolers, hot pellets enter at the top of the cooler while ambient cooling air is channeled into the pellet bed through openings in the discharge grid (Audet, 1995). This setup ensures that the coolest pellets come in contact with the coldest air (cooling step), and the hottest pellets encounter the warmest air (drying step) (Maier and Bakker-Arkema, 1992). As the air moves from the bottom to the top of the cooler, its temperature and water holding capacity increases, leading to a gradual drying and cooling of pellets. There must be a right balance between bed depth and air flow to achieve optimum drying and cooling (Thomas et al., 1997).

Heat from steam addition in the conditioner and frictional heat in the pellet die drive the evaporation of water from the pellets. First, water evaporates from the pellet surface, followed by the migration of water from the center to the exterior due to the pressure gradient (Thomas et al., 1997). During this process, wet bonds formed during conditioning and pelleting are transformed into solid bonds and bridges, while moisture content is reduced (Thomas and Van der Poel, 2020). Additionally, recrystallisation or a glass transition may occur upon cooling, creating fixed binding points between particles (Thomas et al., 1998). These changes can be observed with wet pellets being easily deformable, while dry pellets are hard and brittle.

Benefits of pelleting

It has been well documented that broilers fed pelleted diets consume feed faster (Engberg et al., 2002; Svihus et al., 2004; Corzo et al., 2011), which is the main factor driving body weight gain (**BWG**). Lilly et al. (2011) observed that broilers fed medium-quality pellets (60% pellets: 40% fines) had a higher feed intake (**FI**) and BWG than broilers fed low-quality pellets (30% pellets: 70% fines) and ground pellets (0% pellets: 100% fines). Abdollahi et al. (2011) reported that broilers fed pelleted diets had higher FI by 12% compared to broilers fed mash diets. In addition, pelleting reduces nutrient segregation by preventing birds from selecting larger particles (Forbes and Covasa, 1995). Furthermore, pelleting reduces feed wastage (**FW**), which can be attributed to reduced selective feeding and less particles falling from the bird's beak due to the larger size of pellets compared to mash diets (Abodollahi et al., 2013a). Jensen et al. (1962) studied the feeding pattern of individual birds fed mash and pellets. The authors reported that birds fed mash spent more time eating compared to birds fed pelleted diets (14.3 vs. 4.7%). In another study, Skinner-Noble et al. (2005) reported that birds fed pellets spent less time eating (4.25 vs. 18.81%) and more time resting (62.48 vs. 47.35%) compared to birds fed mash. Furthermore, Jones et al. (1995) suggested that birds fed pelleted diets tend to expend less energy eating, which allow them to use more of the nutrients consumed for growth.

Pelleting represents other advantages related to the feed manufacturing process. According to Thomas and Van der Poel (1996), the flow properties of pelleted feed are better than mash, which is beneficial during transportation and leads to improved flowability in storage silos. Pelleting tends to increase the bulk density of feeds, allowing for a more efficient transportation (Jones et al., 1995). Hussar and Robblee (1962) observed that the density of feed increased from 568.29 kg/m^3 to 707.87 kg/m^3 after pelleting. In addition, pelleting decreases dustiness in both the feed mill and poultry houses by reducing the amount of fines in the feed (Abdollahi et al., 2013a).

EFFECT OF CONDITIONING TEMPERATURES ON BROILER PERFORMANCE

Research evaluating the effects of conditioning temperature on broiler performance have produced inconsistent results. Therefore, there is no standard conditioning temperature widely accepted by the poultry industry, with variations of 10°C typically observed. Previous studies have reported positive (Abdollahi et al., 2011; Teixeira Netto et al., 2019) negative (dos Santos et al., 2020; Perera et al., 2021), or no (Lundblad et al., 2011; Rueda et al., 2022) effects of increasing conditioning temperatures on broiler performance. Improvements are often related to increased pellet quality, while impaired performance is associated with the degradation of heat labile nutrients. According to Abdollahi et al. (2011), the magnitude of the differences observed in broiler performance with varying conditioning temperatures is determined by the balance between negative effects of high conditioning temperatures on nutrient availability and positive effects on pellet quality.

Broiler performance

Due to these opposing effects, broiler trials evaluating pelleted diets conditioned at varying temperatures have not always produced consistent results. Loar II et al. (2014) evaluated three conditioning temperatures (74, 85, and 96°C) and two levels of mixer-added fat (low or high) on broiler performance. In their study, all diets were crumbled to a common feed form to limit the effects of pellet quality and reveal the nutritional effects associated with conditioning temperatures. The authors observed that FCR from 28-42 d increased as conditioning temperatures increased with broilers fed diets conditioned to 74°C having a 3 and 8-point lower FCR compared to broilers fed diets conditioned to 85 and 96°C, respectively. In addition, the authors reported that conditioning to 85 and 96°C reduced the digestibility of Met, Ile, and Pro compared with diets conditioned to 74°C, which could have influenced the negative effects on broiler performance. In another study, Perera et al. (2021) observed that broilers fed diets conditioned to 88°C had the lowest BWG and highest FCR from 1-21 d compared to broilers fed diets conditioned to 60 and 74°C. Creswell and Bedford (2006) reviewed several studies that evaluated varying conditioning temperatures on broiler performance and suggested that conditioning beyond 85°C may impair broiler performance.

Other authors have proposed that the negative effects of high conditioning temperatures on broiler performance are related to increased digesta viscosity (Samarasinghe et al., 2000; Cowieson et al., 2005) and reduced nutrient bioavailability, particularly amino acids (Papadopoulos, 1989), vitamins (Marchetti et al., 1999), and exogenous enzymes (Inborr and Bedford, 1994). Amerah et al. (2013) evaluated the *in vitro* viscosity of feed and jejunal digesta viscosity of birds fed corn-soybean meal-based diets conditioned to 75, 80, and 90°C with or without probiotic supplementation. In their study, the effect of varying conditioning temperatures on diet viscosity was minimal, but they observed that pelleting increased diet viscosity by 35% in the starter and 44% in the finisher diets compared to mash. However, pelleting temperature did not influence jejunal digesta viscosity at 21 or 42 days of age. Cowieson et al. (2005) evaluated the effect of conditioning temperature (80, 85, and 90°C) and exogenous xylanase addition on viscosity of wheat-based diets and broiler performance. During the starter period the authors observed that increasing conditioning temperature from 80 to 90°C increased viscosity by 94% and FCR by 9 points. Perera et al. (2021) reported similar results with high conditioning temperatures in broiler starters fed barley-based diets. They observed that jejunal digesta viscosity was not different between broilers fed diets conditioned to 60 and 74°C (3.13 vs. 3.17 cP) but was higher in broilers fed diets conditioned to 88°C (3.47 cP). The different responses obtained in these studies suggest that the magnitude of the negative effects of higher conditioning temperatures on digesta viscosity depends on the type of ingredients used in the diet. When highly viscous (i.e., high concentration of soluble non-starch polysaccharides) ingredients (e.g., wheat and barley) are used, the negative effects of viscosity may be exacerbated by high conditioning temperatures (Cowieson et al., 2005; Abdollahi et al., 2010).

This could be related to enzyme stability during conditioning and pelleting, as the activity of enzymes used to ameliorate the negative effects of increased digesta viscosity (i.e., xylanase) may be reduced at high conditioning temperatures. Cowieson et al. (2005) evaluated enzyme stability during conditioning and observed that xylanase recovery was reduced from 96% in diets conditioned at 80°C to 71% in diets conditioned at 90°C. Boltz et al. (2020) assessed the thermal stability of a muramidase enzyme under varying conditioning temperatures (77, 82, and 88°C) and observed that enzyme activity was decreased when diets were conditioned to 88°C. Furthermore, Homan et al. (2019) evaluated the effect of three conditioning temperatures (82, 88, and 93°C) on the activity of three phytase products. In general, they observed that phytase activity decreased around 83% as steam conditioning temperatures increased from 82 to 93°C. Similar results were reported by Cavalcanti and Behnke (2004), who evaluated the effect of varying conditioning temperatures on wheat bran endogenous phytase activity. They observed that phytase recovery was 33% when diets were conditioned to 70°C, and conditioning beyond 90°C led to complete phytase degradation. Since conditioning clearly influences enzyme stability, different approaches have been taken to mitigate the negative effects of high conditioning temperatures. These include coating exogenous enzymes with a layer of fat or carbohydrates to withstand the heat and moisture of the pelleting process and developing intrinsically thermostable enzymes (Amerah et al., 2011). Wilkinson et al. (2013) evaluated the heat stability of two thermostable phytases and observed phytase recoveries of 97, 74, and 58% when diets were conditioned to 80, 85, and 90°C, respectively. However, the thermal treatments used in the feed industry can be detrimental to coated or thermostable exogenous enzymes and their stability must be considered when including enzymes in diet formulations.

Furthermore, some studies have reported limited or no effects of conditioning temperature on broiler performance. Salahshour et al. (2023) observed that broilers had a higher BWG from 1-10 days when diets were conditioned to 75°C compared to 65°C, but did not observe any effects of conditioning temperatures on broiler performance from 11-42 days of age. Similar results were reported by Hernandez et al. (2024) when evaluating the effects of conditioning temperatures (80, 84, and 88°C) and metabolizable energy (**ME**) levels (standard energy and -130 kcal/kg reduced energy) on broiler performance. The authors observed a main effect of conditioning temperature on FCR from 1-14 days with broilers fed diets conditioned at 84°C having a higher FCR compared to broilers fed diets conditioned at 80°C. However, conditioning temperature did not influence broiler performance from 14 to 42 days of age in their study. The effects of conditioning temperatures on broiler performance during the starter phase are likely due the nutrient availability rather than by feed quality as broilers are typically fed crumbles during this period. In addition, young birds may be more susceptible to nutrient degradation caused by high conditioning temperatures due to their lower FI. In the study by Rueda et al. (2022), broiler performance from 15 to 49 days of age was not influenced by conditioning temperatures of 71, 77, 82, and 88°C. Lundblad et al. (2011) reported no differences in FCR from 1-21 days between broilers fed diets conditioned to a low temperature (47°C) and high temperature (90°C). Similarly, Abdollahi et al. (2012) did not observe any influence of conditioning temperatures of 60 and 90°C on FCR from 1-35 days.

Increasing conditioning temperatures has also resulted in positive responses on broiler performance. Abdollahi et al. (2011) evaluated two feed forms (mash and pellet) and four conditioning temperatures (20, 60, 75, and 90°C). For the pelleted diets, they observed that birds fed diets conditioned to 60, 75, and 90°C had higher BWG and lower FCR compared to birds fed pellets submitted to dry conditioning (20°C). Furthermore, a study by Teixeira Netto et al. (2019), evaluated five conditioning temperatures (50, 60, 70, 80, and 90°C) with equally spaced intervals of 10°C. They observed a linear effect of conditioning temperature on pellet durability index (**PDI**) ($R^2 = 0.94$) and a quadratic effect on BWG ($R^2 = 0.87$) and FCR ($R^2 = 0.70$). These results suggest that increased pellet quality translates into improved broiler performance up to a threshold where nutrient degradation by high temperatures becomes significant. In addition, other factors such as retention time in the conditioner may influence the response of birds fed diets conditioned to varying temperatures (Massuquetto et al., 2018; Attar et al., 2019) and steam pressure (Cutlip et al., 2008).

Processing yield

Current literature indicates that conditioning temperatures have limited effects on processing yield. Loar II et al. (2014), Salahshour et al. (2023), and Hernandez et al. (2024) reported that varying conditioning temperatures did not influence carcass and parts (breast, tenders, wings, and legs) weight and yield across a range of temperatures from 65 to 96°C. Rueda et al. (2022) evaluated four conditioning temperatures (71, 77, 82, and 88°C) and observed that broilers fed diets conditioned to 82°C had heavier tender weight compared to broilers fed diets conditioned to 71 and 77°C, but no differences were observed in processing yield. These results suggest that processing parameters at meat processing facilities will be mostly unaffected by conditioning temperatures if the effects on broiler performance are limited. It is also possible that the degree of nutrient degradation during conditioning may not be enough to damage amino acids, particularly lysine, to an extent where processing yield is negatively affected.

Nutrient digestibility

Conditioning temperature can induce various chemical changes in feed components due to the combination of heat, water, and pressure (Abdollahi et al., 2013a). One of the feed components that undergoes significant chemical changes during conditioning is starch. According to Imberty et al. (1991), starch granules are water-insoluble and are composed of amylose which is a linear α (1-4) linked glucan) and amylopectin, which consist of α (1-4) linked glucan with α (1-6) branch points. Amylopectin represents up to 70-80% of most cereal starches, while amylose comprises the remaining 20-30%, but some starches (i.e., waxy starch) contain little or no amylose (Rooney and Pflugfelder, 1986). Despite its insoluble characteristics, the starch granules undergo swelling when heated in an aqueous medium. Initially, this swelling is reversible but upon reaching certain temperature, the swelling becomes irreversible, leading to significant alteration of the starch granule (Lund, 1984). This process is known as gelatinization and the temperature at which it occurs is referred as gelatinization temperature. Starch gelatinization and gelatinization temperature are influenced by the characteristics of the starch granule including its source as well as its amylose to amylopectin ratio (Abdollahi et al., 2013a). The occurrence of gelatinization affects starch digestibility as it opens the granule's crystalline structure, allowing enzymes to enter the granules, increasing the susceptibility for amylolytic degradation (Rooney and Pflugfelder, 1986).

The conditioning and pelleting process meets the requirements for starch gelatinization including moisture addition and high temperatures. The extent of gelatinization depends on several factors such as ingredients used in the diet, conditioning temperatures, and pellet die specifications. According to Svihus et al. (2005), the gelatinization of most starches occurs upon heating to temperatures above 80°C in excess water, but this depends on starch source and moisture content. For example, Lund et al. (1984) reported that wheat starch (52-65°C) has a lower gelatinization temperature compared to corn starch (65-77°C). At excess water content, most starches will gelatinize between 50 and 70°C, but under conditions with limited water content (i.e., below 400 g/kg), the gelatinization temperature will increase and be inversely related to water content (Donald, 2001; Parker and Ring, 2001). Since the amount of moisture added during conditioning is around 4%, water is a limiting factor for starch gelatinization during the pelleting process (Thomas et al., 1998). Therefore, several studies have demonstrated that due to the limited moisture content and moderate temperatures during pelleting, the extent of gelatinization on the starch fraction of broiler feeds ranges between 5 and 30% (Skoch et al., 1981; Moritz et al., 2005; Zimonja et al., 2007; Zimonja and Svihus, 2009). In addition, most of the starch gelatinization during pelleting occurs as feed is extruded through the pellet die, due to mechanical shear and higher temperatures caused by frictional heat (Skoch at al., 1981). This shearing action causes starch granules to be fractured, making them more susceptible to enzymatic hydrolysis (Skoch et al., 1983; Zimonja et al., 2008).

Teixeira Netto et al. (2019) reported a linear increase in the apparent ileal digestibility (**AID**) of starch from 91.8% at 50°C to 94.4% at 90°C with increasing conditioning temperature. They suggested that this response may have been caused by the increased amount of steam addition as conditioning temperatures increased, which led to a higher solubilization of the starch fraction. However, higher starch solubilization is not necessarily beneficial for broiler performance, since it may lead to increased diet viscosity, which impairs nutrient absorption in the small intestine (Creswell and Bedford, 2006). Abdollahi et al. (2010) conducted a study in which broilers were fed wheat and corn-based diets conditioned to 60, 75, and 90°C. They observed that in wheat-based diets, AID of starch was lower in broilers fed diets conditioned to 90°C. However, starch digestibility was unaffected by conditioning temperatures in corn-based diets. These findings are likely related to the differences in gelatinization temperature of corn and wheat starch (Lund et al., 1984). Abdollahi et al. (2011) observed that AID of starch was lower in diets subjected to dry pelleting (20°C) compared to diets conditioned to 60 and 90°C. In their study, they evaluated the levels of gelatinized starch (**GS**) and resistant starch (**RS**) in the diets and correlated the observed responses with RS:GS ratio, suggesting that a lower ratio is desired for improved starch utilization. In another study by Abdollahi et al. (2020) broilers fed diets conditioned to 90°C exhibited 1.3% lower AID of starch compared to broilers fed diets conditioned to 60°C. This indicates that conditioning to high temperatures typically results in increased starch gelatinization but may also lead to the formation of resistant starch, which resists enzymatic hydrolysis (Creswell and Bedford, 2006).

Furthermore, energy digestibility is intrinsically related to the digestibility of the starch fraction of a diet. Perera et al. (2021) reported that broilers fed diets conditioned to 88°C had 56 and 43 kcal/kg lower apparent metabolizable energy (**AME**) compared to broilers fed diets conditioned to 60 and 74°C, respectively. Abdollahi et al. (2012) reported that conditioning to 90°C resulted in a decrease of 58 kcal/kg AME compared to conditioning to 60°C. Rueda et al. (2020) reported contrasting results with broilers fed diets conditioned to 71 and 88°C having higher ileal digestible energy compared to broilers fed diets conditioned to 82°C. Generally, authors reporting higher AME with increasing conditioning temperatures attribute this effect to improvements in pellet quality, which results in a higher digestibility of the dietary fractions (Teixeira Netto et al., 2019). On the other hand, reductions in AME are associated with the formation of resistant starch, which may reduce starch and energy digestibility (Creswell and Bedford, 2006).

The heat and moisture applied to feed during conditioning, coupled with shear forces during pelleting, lead to protein denaturation (Thomas et al., 1998). However, the impact of varying conditioning temperatures on crude protein (**CP**) and amino acid digestibility has shown inconsistent results in the literature (Liu et al., 2013; Teixeira Netto et al., 2019; dos Santos et al., 2020; Rueda et al., 2022). In theory, digestibility could be improved when using high conditioning temperatures by inactivating enzyme inhibitors and denaturing proteins, which may expose new sites for enzymatic action (Abdollahi et al., 2013a). Teixeira Netto et al. (2019) reported a linear increase in CP digestibility from 72.35% at 50°C to 79.98% at 90°C. Rueda et al. (2022) observed contrasting results with broilers fed diets conditioned to 71°C exhibiting higher CP digestibility compared to those fed diets conditioned to 77, 82, and 88°C. Dos Santos et al. (2020) observed that AID of CP was higher when conditioning to 85°C for 3 and 9 seconds compared to 65°C, but the opposite response was observed when diets were conditioned to 14 seconds.

From the perspective of amino acid digestibility, research has shown that high conditioning temperatures may impair the digestibility of some amino acids. According to Papadopoulos (1989), high temperatures during feed processing may lead to losses of cysteine, lysine, arginine, threonine, and serine in different protein sources. The degradation of amino acids during feed processing can be attributed to several reasons (Taira, 1966; Hendriks et al., 1994), particularly formation of the Maillard reaction. In the presence of heat and water, free aldehyde groups from reducing sugars such as glucose, lactose, or maltose and free amino groups, particularly the epsilon-amino group of Lys, may combine to form melanoides and increase viscosity (Thomas et al., 1998). In addition, it has been reported that high temperatures and low moisture during pelleting increase the Maillard reaction (Bjorck and Asp, 1983). This reaction may impair the nutritional value of feed due to reduced utilization of amino acids (Hendriks et al., 1994; Thomas et al., 1998). Loar II et al. (2014) evaluated the effect of varying conditioning temperatures (74, 85, and 96°C) on true amino digestibility using cecectomized roosters and reported that conditioning at 85 and 96°C reduced the digestibility of Met, Ile, and Pro by 3 to 5% compared to diets conditioned at 74°C. Although not significant, they also observed that conditioning beyond 85°C tended ($P < 0.10$) to decrease the digestibility of Lys, Val, and Leu by 3 to 6%.

Boltz et al. (2019) reported that increasing conditioning temperatures (77, 82, 88°C) within a retention time of 30-seconds increased the concentration of Met, Lys, and Thr. However, they observed a decrease in amino acid concentration when diets were conditioned at 88°C for 60 seconds. According to the authors, increasing conditioning temperature and time possibly neutralized anti-nutritional factors in the diet (e.g., trypsin inhibitors), but suggested that more severe heat treatment (i.e., 88°C for 60 seconds), could reduce enzyme activity and induce higher protein gelation, resulting in reduced amino acid availability.

Previous researchers have reported an effect of conditioning temperatures on mineral digestibility. The rationale behind this is that steam treatment might soften cell walls, which are further subjected to additional shear and compression forces during pelleting, releasing significant amounts of nutritive components including minerals (Saunders et al., 1969). According to Abdollahi et al. (2013b), high temperatures during pelleting may enhance the digestibility of certain nutrients in corn-based diets such as Ca and P. This improvement could be attributed to the disruption of cell walls, resulting in greater accessibility of cellular contents to digestive enzymes. In this regard, tibia ash is used as an indicator of bone mineralization and some authors have reported increased tibia ash when using increasing conditioning temperatures. Loar II et al. (2014) reported that broilers fed diets conditioned to 96°C exhibited a 6.2% higher tibia ash compared to broilers fed diets conditioned to 74°C. However, other authors have suggested that high conditioning temperatures may impair mineral digestibility. Abdollahi et al. (2020) reported that conditioning to 90°C reduced Ca digestibility by 36.5% compared to diets conditioned to 60°C. Similarly, Perera et al. (2021) observed that broilers fed diets conditioned to 88°C had 16.1% and 19.1% lower P digestibility compared to broilers fed diets conditioned to 74 and 60°C. Homan et al. (2019) reported that increasing conditioning temperatures gradually decreased tibia ash from 45.6% (82°C) to 41.0% (93°C). These responses are generally associated with degradation of exogenous enzymes, particularly phytase, and with higher digesta viscosity caused by a greater degree of solubilization of non-starch polysaccharides (Perera et al., 2021; Homan et al., 2019).

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III. EFFECT OF METABOLIZABLE ENERGY LEVELS AND CONDITIONING TEMPERATURES ON BROILER PERFORMANCE, PROCESSING YIELD, FOOTPAD LESIONS, AND NUTRIENT DIGESTIBILITY FROM 1 TO 42 DAYS OF AGE

ABSTRACT

This study evaluated the main effects and interactions of two metabolizable energy (**ME**) levels and three conditioning temperatures on broiler performance, processing yield, footpad lesions, tibia ash, and nutrient digestibility from 1 to 42 d of age. A total of 1,350 d-old YPM x Ross 708 male broilers were randomly distributed in 54 floor pens and assigned to six treatments (9 replicates/treatment). Diets were formulated to contain two ME levels (standard energy (**SE**) and -130 kcal/kg reduced energy (**RE**)) in all feeding phases. Basal diets for each ME level were manufactured using three conditioning temperatures (80, 84, and 88°C). Feed intake (**FI**), body weight (**BW**), and feed conversion ratio (**FCR**) were determined at 14, 28, 35, and 42 d of age. On d 42, ileal digesta (5 birds/pen) was collected for nutrient digestibility analysis and broilers were processed on d 43. Data were analyzed as a 2 x 3 factorial arrangement using the GLIMMIX procedure of SAS and means separated using Tukey's test. Broilers fed SE had improved FCR ($P < 0.05$) compared to broilers fed RE in every evaluated period. Performance parameters from 15-42 d and processing yields were unaffected ($P > 0.05$) by conditioning temperatures. Apparent ileal digestibility (**AID**) of fat and energy was higher ($P < 0.05$) in broilers fed SE compared to broilers fed RE. Broilers fed diets conditioned to 88°C had lower ($P < 0.05$) AID of Ca and P compared to broilers fed diets conditioned to 80 and 84°C. Overall, most performance parameters were unaffected by conditioning temperatures, but broilers fed SE diets had improved performance and AID of fat and energy compared to broilers fed RE diets.

INTRODUCTION

Broiler meat consumption in the U.S. has steadily increased over the last decade and it is predicted that by 2024 the per capita consumption will be around 45.94 kg (USDA 2023). Therefore, it is important to evaluate nutritional and feed processing strategies to improve nutrient utilization and reduce feeding costs. Pelleting is the most common hydro-thermal processing method used in the manufacturing of broiler diets (Abdollahi et al., 2018). The benefits of feeding pelleted diets (e.g., reduced feed wastage and nutrient segregation and increased feed intake (**FI**), body weight gain, bird uniformity, and feed efficiency) have been well documented (Corzo et al., 2011; Abdollahi et al., 2013a; Goodarzi Boorojeni et al., 2016). However, there are no universally accepted guidelines for pelleting (Cutlip et al., 2008) as conditioning temperatures, retention times in the conditioner, steam pressure, and pellet die specifications can vary among feed mills.

Prior to pelleting, steam addition in the conditioner softens feed particles, activates natural binders present in feed ingredients, increases pellet die lubrication, and reduces frictional heat (Thomas and van der Poel, 1996). However, there is not a standard conditioning temperature and variations of up to 10°C are typically observed. Low conditioning temperatures (< 77°C) can reduce pellet quality and pellet mill efficiency and increase frictional heat as feed is extruded through the pellet die (Skoch et al., 1981). High conditioning temperatures (> 90°C) can improve pellet quality and reduce bacterial load, but can lead to the damage of heat labile nutrients such as vitamins and amino acids and reduce the activity of exogenous enzymes (Loar II et al., 2014; Boltz et al., 2020).

Furthermore, energy represents the greatest cost during feed formulation of poultry diets (Dozier III et al., 2006). Researchers have reported that conditioning temperature influences the apparent ileal digestibility (**AID**) of energy and nutrients in broiler diets (Abdollahi et al., 2012;

dos Santos et al., 2020; Rueda et al., 2022). Dos Santos et al. (2020) reported a lower digestibility of crude protein (**CP**), starch, dry matter (**DM**), and energy as conditioning temperature increased from 65 to 85°C. In addition, Rueda et al. (2022) observed a lower apparent ileal digestible energy (**AIDE**) in diets conditioned to 82°C compared to diets conditioned to 71 and 88°C. Although there is previous research assessing the effects of feed form (i.e., pellet and mash) and nutrient densities on performance and nutrient digestibility of broilers (Abdollahi et al., 2018; Rubio et al., 2019; Massuquetto et al., 2020), the interaction between conditioning temperature and metabolizable energy (**ME**) density is yet to be evaluated. Therefore, the objective of this study was to evaluate the main effects and interactions of two ME levels and three conditioning temperatures on broiler performance, processing yield, footpad lesions, tibia ash, and nutrient digestibility from 1 to 42 d of age.

MATERIALS AND METHODS

Animal care

This broiler trial was conducted at the Auburn University Charles C. Miller, Jr. Poultry Research and Education Center. All procedures involving the use of live birds were reviewed and approved by Auburn University Institutional Animal Care and Use Committee (PRN 2022-4081).

Bird husbandry

A total of 1,350-d-old YPM x Ross 708 male broiler chicks (Aviagen North America, Huntsville, AL) were obtained from a commercial hatchery and randomly distributed in 54 floor pens (25 birds/pen; 0.11 m^2/bird) with used pine shavings top-dressed with new shavings. The research house had a controlled environment and was equipped with a negative pressure ventilation system, exhaust fans, inlet vents, evaporative cooling pads, forced-air heaters, and a control panel for temperature and ventilation management. Feed and water were provided *ad libitum* using a hanging tube feeder and a nipple drinker line (5 nipples/pen). In addition, chicks were provided with supplemental feeders during the first four days. The lightning program consisted of 23L:1D for the first seven days post hatch, 21L:3D from d 7 to 10, and 20L:4D (FC: 0.25) for the remainder of the study. House temperature was set at 33°C during placement and gradually decreased to 18.3°C by 35 d of age to ensure comfort and optimal performance.

Feed formulation, manufacture, and experimental design

This trial evaluated two ME levels and three conditioning temperatures. The ME levels were standard energy (**SE**), which met or exceeded Aviagen recommendations (starter = 2,975 kcal/kg, grower = 3,050 kcal/kg, finisher = 3,100 kcal/kg) for YPM x Ross 708 broilers (Aviagen, 2022) and reduced energy (**RE**) which was formulated to have a reduction of 130 kcal/kg in ME compared to Aviagen recommendations. In addition, diets were conditioned at 80, 84, and 88°C for a total of six dietary treatments. The experimental diets were almost identical in ingredient composition (Table 1) and mainly differed in ME level and conditioning temperature. Broilers were fed starter diets (1-14 d) as crumbles, whereas grower (15-28 d) and finisher (29-42 d) diets were fed as pellets. Furthermore, feed was manufactured approximately seven days prior to the start of each feeding phase.

Diets were manufactured at the Auburn University Poultry and Animal Nutrition Center. Whole corn was ground with a hammermill (Model 11.5 × 38, Roskamp Champion, Waterloo, IA) equipped with a 4.76-mm screen. Ground corn (4.55 kg) was used to premix phytase (500 FTU/kg) in a countertop mixer (Model A-200, The Hobart Mfg. Co., Troy, OH) to ensure a homogenous distribution in the whole batch of feed. Dry ingredients were mixed in a twin shaft mixer (Model 726, Scott Equipment Co, New Prague, MN) using a dry cycle (30 seconds) followed by a wet cycle (120 seconds) after the addition of liquid ingredients. After mixing, mash diets were conditioned at either 80, 84, or 88°C with 40 seconds retention time and pelleted through a 4.0-mm pellet die (Model 1112-4, California Pellet Mill Co., Crawfordsville, IN) with an effective length of 36 mm (length/diameter ratio = 9). To ensure that all diets were conditioned at the selected temperature, the transition between the pellet mill and cooler was closed until pellets reached the target conditioning temperature. Conditioning temperatures were monitored using the computer controller, which indicated the readings obtained by thermometers placed inside the conditioner. The transition to the cooler was opened once the target temperature was reached, and the pelleting process continued. Subsequently, pellets were cooled and dried with ambient air using a counter-flow pellet cooler (Model CC0909, California Pellet Mill Co., Crawfordsville, IN). Starter feeds were crumbled using a crumbler (Model 624SS, California Pellet Mill Co., Crawfordsville, IN) with manual roll adjustment. The amount of mixer-added fat was maintained constant across all treatments to maintain similar pellet quality on every feeding phase. The additional soybean oil needed in the SE treatments was added post-cooling using a mistcoater (Model no. 5TMX, APEC, Lake Odessa, MI) and before crumbling for crumbled diets. Titanium dioxide (**TiO_2**) was included in the finisher diets (29-42 d) as an indigestible marker to assess nutrient digestibility. Each dietary treatment was randomly assigned to 9 replicate pens.

Measurements

During feed bagging, representative pellet samples were taken at evenly spaced intervals for nutrient analysis (Table 1). In addition, samples for pellet quality analysis were taken after the cooler. Pellet quality was determined using pellet durability index (**PDI**) and samples were analyzed no later than two days after feed manufacturing. Pellet durability index was measured using the methodology described in ASAE Standard S269.5 (ASABE, 2012).

Birds and feed were weighed at 1, 14, 28, 35, and 42 d of age to determine body weight (**BW**), FI, and feed conversion ratio (**FCR**). Birds and house conditions were checked twice daily, and temperature and mortality were removed. In addition, mortality weights were recorded and used to adjust FCR. On d 39, 10 birds per pen were randomly selected, wing banded, and marked with a non-toxic dye for processing. On d 42, five birds per pen were randomly selected and euthanized by CO_2 asphyxiation followed by cervical dislocation for ileal digesta and tibia collection. Ileal digesta was collected from 2 cm posterior of Meckel's diverticulum to the 2 cm anterior of the ileal-cecal junction by gently flushing the ileal contents with distilled water. Additionally, sample cups were used to pool the ileal contents of each pen and frozen at -20°C until further analysis. Left tibias were excised from two birds per pen, placed in sample bags and frozen at -20°C until tibia ash analysis was performed.

Birds were processed to determine carcass and parts yield at the Auburn University Fortenberry Processing Plant. Feed was removed 12 h prior to processing, but birds had access to water during the feed withdrawal period. On d 43, birds were transported to processing plant and were shackled, electrically stunned, exsanguinated, scalded, plucked, and eviscerated. Subsequently, carcasses were placed on ice and chilled (4°C) for 3 h before determining chilled carcass weights. On d 44, carcasses were deboned after being stored in ice for 16 h. Stationary cones were used to determine breast (*Pectoralis major*), tenders (*Pectoralis minor*), wings, and legs weight and yield. A leg included the drumstick and thigh, whereas a wing included the wing tip, wing portion, and drumette. Carcass yield was calculated relative to live BW of birds on d 42 and chilled carcass weight was used to calculate parts yield.

Footpad lesions and litter moisture

On d 42, all birds were assessed for footpad lesions using a modified four-point scale. Score 0 represented no lesions, score 1 indicated lesions covering less than 25% of the footpad area, score 2 were lesions that covered 25-50% of the footpad area, and score 3 for lesions covering more than 50% (Welfare Quality, 2009; Rushen et al., 2011). Representative litter samples were collected on d 41. Samples were collected from four locations within the pen, avoiding areas directly below drinker lines. Litter moisture was analyzed in duplicates according to the procedures described in AOAC Official Method 934.01 (AOAC 2006). For this analysis, 2 g of litter sample were placed on an aluminum pan and dried in an oven at 105°C for 5 h. Then, samples were allowed to cool in a desiccator, dry litter weight was recorded, and litter moisture was calculated with the following equation:

$$\% \, moisture = 100 \, x \, \frac{wt \; loss \; on \; drying}{wt \; test \; portion}$$

Tibia ash analysis

Tibias collected during necropsy were used to assess bone mineralization. Frozen tibias were thawed at room temperature and cleaned by removing tissue and cartilaginous caps. Clean tibias were weighed, and a digital caliper was used to measure tibia length and width. Subsequently, each bone was manually broken into smaller pieces and individually packed with filter cloth. Tibias were exposed to sequential extractions for 24 h in 200-proof ethanol followed by another 24 h in anhydrous ether using a Soxhlet apparatus (VWR International, Radnor, PA). Ethanol was used to remove water and non-polar lipids, whereas polar lipids were removed with anhydrous ether. After the sequential extractions, tibias were allowed to dry for a minimum of 24 h and weighed for subsequent ashing at 600°C for 12 h in a muffle furnace as described by Hall et al. (2003). Lastly, ashed tibias were weighed to calculate tibia ash.

Nutrient digestibility analyses

Titanium dioxide was included at 0.5% of the diet as an indigestible marker on the finisher phase (29-42 d) to calculate AID of nutrients. Ileal digesta samples collected on d 42 were lyophilized in a Virtis Genesis Pilot Lyophilizer (SP Industries, Warminster, PA) and ground using an electric coffee grinder (Capresso 560.4 Infinity, Montvale, NJ) on the finest setting. After grinding, dried ileal digesta and feed samples were sent to a commercial laboratory (Dairy One Forage Laboratory, Ithaca, NY) to be analyzed for CP (AOAC International (2006) Official Method 990.03), crude fat (method 2003.06; AOAC International, 2006), and minerals (Wolf et al. (2003) and CEM Application Notes for Acid Digestion). A portion of the ileal digesta and feed samples was retained for analysis of gross energy (**GE**) and TiO_2 concentration (Short et al., 1996). Gross energy was determined using an adiabatic bomb calorimeter (model no. 6400, Parr Instruments, Moline, IL) standardized with benzoic acid. Apparent ileal digestibility of CP, fat, minerals, and energy was calculated using an equation adapted from Stein et al. (2007):

$$Nutrient\ AID, \% = \left[\frac{\left(\frac{Nutrient}{TiO_2}\right)_{diet} - \left(\frac{Nutrient}{TiO_2}\right)_{digesta}}{\left(\frac{Nutrient}{TiO_2}\right)_{diet}}\right] \times 100$$

where $\left(\frac{Nutrient}{TiO_2}\right)$ represents the ratio of CP, fat, minerals, and energy to TiO_2 in ileal digesta or diet. In addition, GE digestibility (%) values obtained from this equation were multiplied by the GE content of feed to calculate AIDE in units of kcal/kg on a DM basis.

Statistical analyses

For this trial, data were analyzed as a 2 x 3 factorial (ME level x conditioning temperature) arrangement in a completely randomized design to evaluate main effects and interactions. Floor pens were considered as the experimental unit and each treatment was represented by 9 replicate pens. When applicable, percentage data was arcsine transformed before statistical analysis. Data were analyzed using the GLIMMIX procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC) with the following model:

$$Y_{ijk} = \mu + \tau_i + \beta_j + (\tau\beta)_{ij} + \varepsilon_{ijk}$$

where Y_{ijk} is the observed response of the birds in each pen; $\boldsymbol{\mu}$ is the overall mean; $\boldsymbol{\tau_i}$ are the factor effects of the $\boldsymbol{i}$th level of ME; β_j are the identically and independently normally distributed effects of the jth conditioning temperature; $(\tau\beta)_{ij}$ is the interaction between ME level and conditioning temperature at the $\boldsymbol{i}$th and jth level; and ε_{ijk} are the normally distributed random errors with mean 0 and variance α^2. In addition, means were separated using Tukey's HSD Test and statistical significance was considered at $P \leq 0.05$.

RESULTS AND DISCUSSION

Feed quality

Feed quality was measured using PDI (Table 2) and these results were considered as an estimation of the feed quality that the birds received. Pellet durability was improved ($P < 0.05$) with increasing conditioning temperatures during the grower and finisher periods. Grower diets conditioned to 80°C presented the lowest PDI, whereas diets conditioned to 88°C had the highest and diets conditioned at 84°C were intermediate. Similar results were obtained for finisher feed with diets conditioned to 88°C having the highest ($P < 0.05$) PDI compared to diets conditioned to 80 and 84°C. The effects of conditioning temperature on pellet quality have been extensively reviewed and the results of this trial agree with previous studies which reported improvements in pellet quality with increasing conditioning temperatures (Cutlip et al., 2008; Abdollahi et al., 2010; Tillman et al., 2020). Loar II et al. (2014) reported 22% higher PDI when diets were conditioned at 96°C compared to diets conditioned at 74°C. This increase in pellet quality can be attributed to the heat and moisture added by steam during the conditioning process. Higher steam addition increases heat and moisture penetration into the mash feed. Starch and tertiary structure of proteins are modified during the feed conditioning process, which causes starch gelatinization and protein plasticization (Briggs et al., 1999; Muramatsu et al., 2015). The conditioning process also leads to the softening of feed particles and activation of natural binders, which causes a stronger particle adhesion due to structural changes in starch and protein molecules (Behnke, 2001).

Broiler performance

Broiler performance variables are shown in Table 3. No significant interactions were observed between conditioning temperatures and ME levels ($P > 0.05$). However, ME level influenced BW, FI, and FCR. Broilers fed SE diets had a higher BW than broilers fed RE diets on d 14 and 28 ($P < 0.05$). In addition, broilers fed RE diets had higher FI at 35 and 42 d of age ($P < 0.05$). Furthermore, broilers fed SE diets had lower FCR compared to broilers fed RE diets on every evaluated period ($P < 0.05$). Improvements in FCR ranged from a 3-point difference from 1 to 14 d to a 7-point difference from 1 to 42 d of age.

In the present study, broilers fed SE diets had improved performance compared to broilers fed RE diets. These results agree with previous research that evaluated varying levels of dietary ME on broiler performance (Ghazalah et al., 2008; Firman et al., 2010; Jahanian and Ashnagar, 2018). Moritz et al. (2003) evaluated the effect of energy (NRC recommendations and 5% less) and added moisture in the mixer to obtain diets with varying energy densities on broiler performance from 21 to 42 d of age. The authors reported that broilers fed recommended energy diets had a lower FCR than broilers fed low energy diets. Similarly, Jahanian and Ashnagar (2018) evaluated three levels of dietary ME (control, +100, and +200 kcal/kg) and observed that broilers fed the highest ME level had the lowest FI and highest average daily gain from 29-42 d of age. In addition, the authors reported a 12-points lower FCR during the finisher phase when the ME of the diet increased by 200 kcal/kg in comparison to broilers fed the control diet. Additionally, it has been reported that broilers can adjust their FI based on the ME level of the diet (Leeson et al., 1996; Albuquerque et al., 2003). In the present study, broilers fed RE diets had higher FI at 35 and 42 d of age, but no differences were observed at 14 and 28 d of age. This response suggests that broilers fed energy deficient diets can increase feed consumption to compensate lower dietary energy levels.

In addition, a main effect of conditioning temperature was observed for FCR from 1-14 d of age ($P < 0.05$). Differences were observed with broilers fed diets conditioned at 80°C having the lowest FCR in comparison to broilers fed diets conditioned at 84°C, which had the highest FCR, and broilers fed diets conditioned to 88°C were intermediate. Abdollahi et al. (2012) assessed the effect of pellet binder and/or moisture addition on the performance of broilers fed diets conditioned at two different temperatures (60 and 90°C) with a retention time of 30 seconds. The authors reported similar results to the present study, as broilers fed diets conditioned at 60°C had lower FCR only during the starter period compared to broilers fed diets conditioned at 90°C. Cutlip et al. (2008) obtained contrasting results and reported that broilers fed diets conditioned to a high temperature (93.3°C) had lower FCR from 21 to 39 days compared to broilers fed diets conditioning at 82.2°C. In their study, a short retention time was used (10 seconds), which may have allowed for the use of higher conditioning temperatures without affecting thermolabile nutrients.

Improvements in broiler performance associated with higher conditioning temperatures are often related to increased pellet quality. However, in the present study, broilers were fed crumbles during the starter period so any effects of conditioning temperature on broiler performance may be attributed to the nutrient availability of diets (Abdollahi et al., 2012). Thermal processing during conditioning can lead to the damage of heat labile nutrients such as vitamins and amino acids and reduce the activity of exogenous enzymes (Silversides and Bedford, 1999; Boltz et al., 2020) and young birds may be more susceptible to these negative effects due to their lower feed consumption.

Carcass characteristics

No significant interactions were observed between ME levels and conditioning temperatures ($P > 0.05$) for any of the evaluated processing parameters (Table 4). However, a significant main effect of ME level was observed on breast yield and wing weight ($P < 0.05$). Wing weight was 1.47% higher in broilers fed SE diets compared to broilers fed RE diets ($P < 0.05$), but broilers fed SE diets had a lower breast meat yield than broilers fed RE diets ($P < 0.05$). The increased breast yield in broilers fed RE diets was likely influenced by amino acid intake. Since all diets were formulated to have the same amino acid density, but broilers fed RE had a higher FI, these broilers consumed 2.8% more digestible lysine as well as other AA. It has been reported that amino acid density influences breast meat development (Kerr et al., 1999; Dozier III et al., 2010).

Furthermore, processing parameters were essentially unaffected by conditioning temperatures ($P>0.05$). These results agree with previous studies, which have reported limited or no effects of varying conditioning temperatures on carcass characteristics (Loar II et al., 2014; Rueda et al., 2022). Rueda et al. (2022) reported no differences on processing parameters when diets were conditioned at 71, 77, 82, and 88°C. In addition, Ebbing et al. (2022) reported that expander conditioning prior to pelleting did not affect carcass parts (breast, tenders, wings, legs) yield. The lack of response in processing parameters can be attributed to the limited effect of conditioning temperatures in broiler performance variables.

Footpad lesions and litter moisture

In general, broilers fed SE diets had lower incidence of footpad lesions compared to broilers fed RE diets (Table 5) with differences between SE and RE-fed broilers being observed for scores 0, 2, and 3 ($P < 0.05$). Broilers fed SE diets had a higher proportion of score 0 and a lower percentage of scores 2 and 3 compared to broilers fed RE diets. These results are in close agreement with results reported by Zuowei et al. (2011), in which the average footpad burn score was higher for broilers fed diets with low ME (2,800, 2,900, and 3,000 kcal/kg) compared to broilers fed high ME (2,950, 3,050, and 3,150 kcal/kg) diets. Similarly, de Jong et al. (2015) assessed the effect of energy level (recommended and -200 kcal/kg) and observed higher footpad dermatitis (**FPD**) and hock burn scores in broilers fed low energy diets compared to broilers fed high energy diets.

According to Sheperd and Fairchild (2010), FPD is a condition that causes necrotic lesions on the plantar surface of the footpad in growing broilers, and it is widely accepted that litter moisture is one of the factors that influences FPD severity (Swiatkiewicz et al., 2017). A possible explanation for the higher incidence of footpad lesions in broilers fed RE diets is the increased FI observed when feeding diets with RE. Since all diets were formulated to be identical in nutrient content and only differed in ME level, higher feed consumption would translate into a greater intake of CP and minerals, which are nutrients that can increase water consumption and excreta moisture. It has been reported that higher protein levels in the diet (Nagaraj et al., 2007) and increased dietary sodium (Cengiz et al., 2012) can increase litter moisture and thus, increase the incidence of footpad lesions. However, in the present study no differences were observed on d 41 litter moisture between SE and RE treatments ($P > 0.05$). It is possible that the ventilation program was efficient in removing excess moisture from the litter. Additionally, conditioning temperature influenced the incidence of footpad lesions with score 3 ($P < 0.05$). Broilers fed diets conditioned at 80°C had lower incidence of footpad lesions compared to broilers fed diets conditioned to 84°C and broilers fed diets conditioned to 88°C were intermediate. A similar response was observed for d 41 litter moisture with diets conditioned to 84°C having the highest litter moisture compared to diets conditioned to 80 and 88°C, which may explain the higher incidence of footpad lesions in broilers fed diets conditioned to 84°C.

Tibia parameters

For all tibia parameters (Table 6), no interactions were observed between conditioning temperatures and ME levels ($P > 0.05$). Tibia weight, length, and width were not influenced by conditioning temperature or ME level ($P > 0.05$). However, ME level and conditioning temperature influenced tibia ash. Broilers fed SE diets had higher ($P < 0.05$) tibia ash than broilers fed RE diets by 0.7 percentage points. Furthermore, broilers fed diets conditioned to 80°C had lower tibia ash than broilers fed diets conditioned to 84 and 88°C ($P < 0.05$). Previous research has reported inconsistent results when assessing the effect of ME levels or conditioning temperatures on bone mineralization (Venalainen et al., 2006; Wilkinson et al., 2013; Homan et al., 2019). Venalainen et al. (2006) evaluated two ME levels, which had a difference of 240 kcal/kg between the high and low ME treatments. They observed that tibia length, width, and weight were greater in broilers fed higher ME diets compared to broilers fed low ME diets, but reported a higher tibia ash on broilers fed low ME diets. Kirkpinar et al. (2006) did not observe differences in tibia ash between broilers fed diets conditioned to 65, 75, and 85°C. Additionally, Homan et al. (2019) reported that tibia ash decreased as conditioning temperatures increased. In their study, broilers fed diets conditioned to 82°C had the higher tibia ash compared to broilers fed diets conditioned to 88 and 93°C. In contrast, Loar II et al. (2014) observed that broilers fed diets conditioned to

74°C presented a lower tibia ash by 1.8 percentage points compared to broilers that were fed diets conditioned to 96°C.

According to Abdollahi et al. (2013b) higher conditioning temperatures prior to pelleting may enhance the digestibility of Ca and P. High temperatures could lead to the disruption of cell walls of cereals which encapsulate significant amounts of nutritive components (Saunders et al., 1969; Abdollahi et al., 2013b). Nevertheless, in the present study a reduction in the digestibility of Ca and P was observed with increasing conditioning temperatures (Table 7).

Nutrient digestibility

Apparent ileal digestibility of CP (Table 7) was not influenced by ME level or conditioning temperatures ($P > 0.05$). Fat digestibility increased by 3.18% ($P < 0.05$) when broilers were fed SE diets compared to broilers fed RE diets. In addition, AIDE was higher ($P < 0.05$) by 210 kcal/kg in broilers fed SE diets compared to broilers fed RE diets. These results are in partial agreement with the report by Attia et al. (2021), who fed a standard energy diet based on the breeder recommendations and diets with a reduction of 50, 100, and 150 kcal/kg. The authors did not observe differences on the coefficients of apparent ileal digestibility (**CAID**) of CP and GE of broilers at 42 d of age. Massuquetto et al. (2020) assessed the effects of feed form (mash and pellet) and energy level (3,040, 3,120, 3,200, and 3,280 kcal/kg) on nutrient digestibility of broilers from 35 to 47 d of age. The authors reported that energy level did not influence the CAID of CP but observed that broilers fed the 3,200 kcal/kg diet had a higher CAID of GE than broilers fed the 3,120 kcal/kg diet.

In the present study, the higher fat digestibility and AIDE observed in broilers fed SE diets may be attributed to higher inclusion of soybean oil. Diets with SE contained more supplemental fat compared to RE diets. According to Kil at al. (2010), extracted fat sources are more readily utilized and have a more direct path to digestion and absorption compared to lipids contained within the cell wall of corn and other ingredients. The encapsulation of intact fat in cell membranes makes it more resistant to the formation of emulsions and enzymatic digestion than supplemental fat (Bach Knudsen et al., 1993), which could have caused the lower fat digestibility and AIDE in broilers fed RE diets.

Regarding mineral digestibility, broilers fed SE diets had a lower ($P < 0.05$) digestibility of Ca, P, and K than broilers fed RE diets. Abdollahi et al. (2018), reported similar results when evaluating the effects of varying levels of nutrient density (very low, low, medium, high, and very high) and feed form (mash and pellet) on the nutrient digestibility of broilers. Their medium density (3,000 kcal/kg) diet was formulated to meet the breeder recommendations and broilers fed this diet in a pellet form had a lower Ca digestibility than broilers fed the very low density (2,800 kcal/kg) pelleted diet. In addition, they observed a higher CAID of P in broilers fed the very low-density pelleted diet compared to broilers fed the low density (2,900 kcal/kg) pelleted diet. Similarly, Mtei et al. (2019), reported a higher P digestibility in broilers fed a high fiber and low energy (2,900 kcal/kg) diet compared to broilers fed a low fiber and higher energy (3,000 kcal/kg) diet. The lower Ca, P, and K digestibilities observed in broilers fed SE diets may have been caused by the formation of soaps between free fatty acids and minerals in the gut lumen (Zeits et al., 2015; Furhmann and Kamphues, 2016). The higher inclusion of soybean oil in SE diets could have led to a higher availability of free fatty acids, which could have caused an increased formation of soaps. The formation of soaps may reduce mineral digestibility since the formed complexes are eliminated in the excreta.

Conditioning temperatures did not influence CP and fat digestibility and AIDE ($P < 0.05$), but it influenced mineral digestibility. Broilers fed diets conditioned to 88°C had the lowest ($P <$

0.05) Ca and P digestibility compared to broilers fed diets conditioned to 80 and 84°C. Additionally, broilers fed diets conditioned to 80°C had higher ($P < 0.05$) AID of K compared to broilers fed diets conditioned to 84 and 88°C. Furthermore, an interaction between ME level and conditioning temperature ($P < 0.05$) was observed for Ca digestibility. In broilers fed RE diets, Ca digestibility decreased as conditioning temperatures increased. Broilers fed RE diets conditioned to 80°C had a higher ($P < 0.05$) Ca digestibility than broilers fed RE diets conditioned to 88°C. Previous studies have evaluated the effects of varying conditioning temperatures and other thermal treatments on the nutrient digestibility of broilers, but the findings have been inconsistent. Teixeira Netto et al. (2019) observed that increasing conditioning temperature (50, 60, 70, 80, and 90°C) improved the CAID of starch, DM, and CP of broiler diets. In contrast, dos Santos et al. (2020) reported that high conditioning temperature (85°C) with retention times higher than 20 seconds may compromise nutrient digestibility. Additionally, in the study by Rueda et al. (2022) fat digestibility was not influenced by conditioning temperatures, but CP digestibility was higher when broilers consumed diets conditioned to 71°C compared to broilers fed diets conditioned to 77, 82, and 88°C.

Although no negative effects in the AID of fat, CP, and energy were observed in the present study, results reported by previous researchers suggest that increasing conditioning temperatures may impair mineral digestibility in broiler diets (Abdollahi et al., 2020; Perera et al., 2021). Abdollahi et al. (2020) reported a 37% reduction in Ca digestibility of broilers fed wheat-based diets in response to increasing conditioning temperatures from 60 to 90°C. In addition, Perera et al. (2021) observed lower CAID of P in 21-d-old broilers fed diets conditioned to 88°C compared to broilers fed diets conditioned to 74 and 60°C. Previous authors have discussed that the reduction of mineral digestibility in response to increasing conditioning temperatures may be attributable to exogenous phytase degradation (Vande Ginste and De Schrijver, 1998) or higher digesta viscosity caused by increased solubilization of non-starch polysaccharides (Perera et al., 2021). However, there is a paucity of research that evaluates the effects of conditioning temperatures on mineral digestibility and further research may be needed to better understand these findings.

CONCLUSIONS

1. Broilers fed standard energy diets had improved growth performance, tibia ash, fat digestibility, AIDE, and less incidence of footpad lesions.
2. Breast yield was higher in broilers fed reduced energy diets, likely due to higher amino acid intake.
3. Most of the performance and processing parameters evaluated in this study were unaffected by conditioning temperatures.
4. Increasing conditioning temperatures led to higher tibia ash but reduced mineral digestibility.

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Table 3. 1 Ingredient and nutrient composition of standard energy (SE) and reduced energy (RE) dietary treatments fed to YPM x Ross 708 male broilers from 1 to 42 d of age.

Ingredient, % as-fed (unless otherwise noted)	Starter, 1 to 14 d		Grower, 15 to 28 d		Finisher, 29 to 42 d	
	SE	RE	SE	RE	SE	RE
Corn	50.48	53.95	55.28	58.56	57.01	60.29
Soybean meal	37.37	36.80	32.13	31.73	29.30	28.90
Distilliers dried grains with solubles (DDGS)	5.00	5.00	5.00	5.00	5.00	5.00
Soybean oil	3.54	0.62	4.34	1.45	5.72	2.84
Dicalcium phosphate	1.23	1.23	1.02	1.02	0.88	0.88
Calcium carbonate	1.06	1.06	0.98	0.99	0.93	0.93
Salt	0.35	0.35	0.35	0.35	0.35	0.35
DL-Methionine	0.35	0.34	0.31	0.31	0.30	0.29
L-Lysine	0.21	0.22	0.21	0.21	0.18	0.19
L-Threonine	0.14	0.14	0.12	0.12	0.10	0.10
Trace mineral premix[1]	0.10	0.10	0.10	0.10	0.10	0.10
Vitamin premix[2]	0.10	0.10	0.08	0.08	0.05	0.05
Choline chloride	0.07	0.07	0.07	0.07	0.08	0.07
Quantum Blue®[3], g/kg	0.10	0.10	0.10	0.10	0.10	0.10
Calculated nutrients, % as-fed (unless otherwise noted)						
AMEn, kcal/kg	3,000	2,870	3,100	2,970	3,200	3,070
Crude protein	23.32	23.30	21.10	21.14	19.82	19.86
Digestible Lys	1.28	1.28	1.15	1.15	1.06	1.06
Digestible TSAA	0.95	0.95	0.87	0.87	0.83	0.83
Digestible Thr	0.86	0.86	0.77	0.77	0.71	0.71
Calcium	0.96	0.96	0.87	0.87	0.81	0.81
Available P	0.48	0.48	0.44	0.44	0.41	0.41
Analyzed nutrients, % as-fed						
Crude protein	24.77	23.48	23.53	23.78	22.40	22.33
Fat	6.37	3.94	7.86	4.60	9.84	5.98

[1] 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 (ethylenediaminedihydroxide), 1.4 mg; and Se (sodium selenite), 0.3 mg.

[2] Vitamin premix included per kg of diet: Vitamin A (Vitamin A acetate), starter: 18,740 IU, grower: 14,992 IU, finisher 9,370 IU; Vitamin D (cholecalciferol), starter: 6,614 IU, grower: 5,291 IU, finisher: 3,307 IU; Vitamin E (DL-alpha tocopherol acetate), starter: 78 IU, grower: 66 IU, finisher: 47 IU; menadione (menadione sodium bisulfate complex), starter: 4 mg, grower: 3 mg, finisher: 2

mg; Vitamin B12 (cyanocobalamin), starter: 0.03 mg, grower: 0.03 mg, finisher: 0.02 mg; folacin (folic acid), starter: 4.14 mg, grower: 3.44 mg, finisher 2.55 mg; D-pantothenic acid (calcium pantothenate), starter: 39 mg, grower: 32 mg, finisher: 23 mg; riboflavin (riboflavin), starter: 24 mg, grower: 19 mg, finisher: 13 mg; niacin (niacinamide), starter: 108 mg, grower: 90 mg, finisher: 63 mg; thiamin (thiamine mononitrate), starter: 8.3 mg, grower: 7.2 mg, finisher: 5.6 mg; D-biotin (biotin), starter: 0.33 mg, grower: 0.28 mg, finisher: 0.22 mg, and pyridoxine (pyridoxine hydrochloride), starter: 14 mg, grower: 13 mg, finisher: 10 mg.

[3] Quantum Blue® (AB Vista, Marlborough, Wiltshire, UK) provided 500 FTU/kg of phytase activity per kg of diet.

Table 3. 2 Pellet durability index (PDI) of grower and finisher diets subjected to different conditioning temperatures.

Temperature (°C)	PDI (%)[2]	
	Grower	Finisher
80	87.37^{c}	78.57^{b}
84	88.70^{b}	78.43^{b}
88	90.40^{a}	80.63^{a}
P-value	<.001	0.010
SEM[1]	0.37	0.55

$^{a\text{-}c}$Least square means within a column with different superscripts differ significantly ($P \leq 0.05$)

[1] SEM= Standard error of the mean

[2] PDI = Pellet durability index was calculated by dividing weight of pellets after tumbling/weight of pellets before tumbling and multiply it by a 100. A total of 4 samples collected for every treatment at evenly spaced intervals after cooler

Table 3. 3 Growth performance of YPM x Ross 708 male broilers fed diets with varying ME levels and conditioning temperatures from 1 to 42 d of age.

Temperature	Energy	BW (g/bird)				Feed Intake (g/bird)				FCR (g:g)			
		Days of age											
		14	28	35	42	1 to 14	1 to 28	1 to 35	1 to 42	1 to14	1 to 28	1 to 35	1 to 42
80°C	Reduced[2]	468	1,659	2,505	3,344	541	2,274	3,591	5,031	1.15	1.36	1.42	1.51
	Standard[3]	479	1,727	2,565	3,432	547	2,274	3,554	4,977	1.12	1.31	1.38	1.44
84°C	Reduced	470	1,713	2,554	3,426	553	2,301	3,669	5,138	1.18	1.35	1.44	1.51
	Standard	470	1,721	2,563	3,416	538	2,258	3,536	4,934	1.14	1.31	1.38	1.44
88°C	Reduced	467	1,693	2,526	3,361	541	2,317	3,650	5,076	1.16	1.36	1.43	1.50
	Standard	485	1,743	2,574	3,411	543	2,276	3,552	4,912	1.13	1.30	1.38	1.45
SEM[1]		7	20	27	43	8	23	40	47	0.009	0.006	0.006	0.009
Main Effects													
80°C		473	1,693	2,535	3,388	544	2,274	3,573	5,004	1.137^{b}	1.33	1.40	1.47
84°C		470	1,717	2,558	3,421	546	2,279	3,603	5,036	1.158^{a}	1.33	1.41	1.48
88°C		476	1,718	2,550	3,386	542	2,296	3,601	4,994	1.144^{ab}	1.33	1.40	1.47
SEM		5	14	18	28	5	16	25	33	0.006	0.004	0.004	0.006
	Reduced	468^{b}	1,689^{b}	2,528	3,377	545	2,297	3,637^{a}	5,082^{a}	1.16^{a}	1.36^{a}	1.43^{a}	1.51^{a}
	Standard	478^{a}	1,730^{a}	2,567	3,420	543	2,269	3,548^{b}	4,941^{b}	1.13^{b}	1.31^{b}	1.38^{b}	1.44^{b}
SEM		4	11	15	23	4	13	20	26	0.005	0.003	0.003	0.004
P-values													
Temperature		0.615	0.334	0.649	0.555	0.867	0.563	0.566	0.619	0.037	0.836	0.610	0.834
Energy		0.040	0.010	0.067	0.165	0.701	0.119	0.002	0.004	<.001	<.001	<.001	<.001
Temperature x Energy		0.338	0.290	0.587	0.409	0.273	0.499	0.342	0.227	0.676	0.272	0.408	0.507

[a-b] Least square means within a column with different superscripts differ significantly ($P \leq 0.05$)

[1] SEM= Standard error of the mean

[2] ME levels (kcal/kg) - Starter 2870, Grower 2970, Finisher 3070

[3] ME levels (kcal/kg) - Starter 3000, Grower 3100, Finisher 3200

Table 3. 4 Carcass and parts yield of YPM x Ross 708 male broilers fed diets with varying ME levels and conditioning temperatures from 1 to 42 d of age.

Temperature	Energy	Cold Carcass		Breast		Tenders		Wings		Legs	
		(g)	(%)	(g)	(%)	(g)	(%)	(g)	(%)	(g)	(%)
80°C	Reduced[2]	2,736	79.22	799	29.51	159	5.83	266	9.80	743	27.29
	Standard[3]	2,779	78.66	808	29.13	158	5.68	273	9.85	761	27.49
84°C	Reduced	2,733	78.27	810	29.54	156	5.71	270	9.91	749	27.52
	Standard	2,733	78.69	794	29.07	158	5.80	268	9.84	748	27.46
88°C	Reduced	2,746	78.87	814	29.78	159	5.84	267	9.73	754	27.43
	Standard	2,770	78.69	807	29.12	160	5.76	275	9.92	764	27.56
SEM[1]		24	0.64	10	0.23	2	0.07	2	0.07	7	0.17
Main Effects											
80°C		2,757	78.94	804	29.32	158	5.76	269	9.83	752	27.39
84°C		2,733	78.48	802	29.30	157	5.76	269	9.88	749	27.49
88°C		2,758	78.78	811	29.45	159	5.80	271	9.83	759	27.49
SEM		17	0.44	7	0.16	1	0.05	2	0.04	5	0.12
	Reduced	2,738	78.79	808	29.61^{a}	158	5.79	268^{b}	9.81	748	27.41
	Standard	2,761	78.68	803	29.11^{b}	159	5.75	272^{a}	9.87	758	27.50
SEM		13	0.36	6	0.13	1	0.04	1	0.04	4	0.09
					P-values						
Temperature		0.456	0.778	0.653	0.752	0.623	0.772	0.668	0.666	0.326	0.762
Energy		0.238	0.839	0.583	0.005	0.796	0.441	0.022	0.205	0.102	0.475
Temperature x Energy		0.642	0.767	0.432	0.805	0.718	0.177	0.049*	0.118	0.378	0.706

[a-b] Least square means within a column with different superscripts differ significantly ($P \le 0.05$)

[1] SEM= Standard error of the mean

[2] ME levels (kcal/kg) - Starter 2870, Grower 2970, Finisher 3070

[3] ME levels (kcal/kg) - Starter 3000, Grower 3100, Finisher 3200

*Overall model was significantly different; however, Tukey's HSD was unable to separate means

Table 3. 5 Incidence of footpad lesions and litter moisture of YPM x Ross 708 male broilers fed diets with varying ME levels and conditioning temperatures from 1 to 42 d of age.

Temperature	Energy	Footpad Score (%)				Litter Moisture (%)
		0	1	2	3	D 41
80°C	Reduced[2]	37.37	22.80	34.22	5.60	34.10
	Standard[3]	63.25	20.83	14.38	0.00	35.87
84°C	Reduced	26.79	22.98	41.49	11.34	41.74
	Standard	49.50	21.67	25.39	4.20	38.62
88°C	Reduced	31.62	24.93	37.36	6.09	31.10
	Standard	55.01	19.22	21.79	3.65	34.26
SEM[1]		7.56	3.65	5.38	2.38	2.00
Main Effects						
80°C		50.31	21.81	24.30	2.80^{b}	34.99^{b}
84°C		38.14	22.33	33.44	7.77^{a}	40.18^{a}
88°C		43.32	22.07	29.58	4.87^{ab}	32.68^{b}
SEM		5.04	2.43	3.48	1.57	1.37
	Reduced	31.93^{b}	23.57	37.69^{a}	7.68^{a}	35.64
	Standard	55.92^{a}	20.57	20.52^{b}	2.62^{b}	36.25
SEM		4.03	1.94	2.74	1.28	1.11
P-values						
Temperature		0.257	0.966	0.274	0.012	0.001
Energy		0.001	0.484	<.001	0.016	0.702
Temperature x Energy		0.982	0.648	0.868	0.474	0.203

[a-b] Least square means within a column with different superscripts differ significantly ($P \le 0.05$)

[1] SEM= Standard error of the mean

[2] ME levels (kcal/kg) - Starter 2870, Grower 2970, Finisher 3070

[3] ME levels (kcal/kg) - Starter 3000, Grower 3100, Finisher 3200

Table 3. 6 Tibia parameters of YPM x Ross 708 male broilers fed diets with varying ME levels and conditioning temperatures at 42 d of age.

Temperature	Energy	Tibia Width (mm)	Tibia Weight (g)	Tibia Length (mm)	Tibia Ash (%)
80°C	Reduced[2]	9.29	16.32	99.21	50.25
	Standard[3]	8.79	16.09	101.41	50.74
84°C	Reduced	9.22	16.90	100.94	51.28
	Standard	9.29	17.70	103.42	52.03
88°C	Reduced	9.47	17.20	102.00	51.24
	Standard	9.36	17.21	100.31	52.09
SEM[1]		0.28	0.67	1.44	0.44
Main Effects					
80°C		9.04	16.21	100.31	50.49^{b}
84°C		9.25	17.30	102.18	51.66^{a}
88°C		9.41	17.21	101.16	51.67^{a}
SEM		0.19	0.46	0.96	0.29
	Reduced	9.33	16.81	100.72	50.92^{b}
	Standard	9.14	17.00	101.72	51.62^{a}
SEM		0.15	0.37	0.78	0.24
			P-values		
Temperature		0.352	0.175	0.380	0.007
Energy		0.392	0.710	0.357	0.037
Temperature x Energy		0.537	0.707	0.207	0.903

[a-b] Least square means within a column with different superscripts differ significantly ($P \leq 0.05$)

[1] SEM= Standard error of the mean

[2] ME levels (kcal/kg) - Starter 2870, Grower 2970, Finisher 3070

[3] ME levels (kcal/kg) - Starter 3000, Grower 3100, Finisher 3200

Table 3. 7 Apparent ileal nutrient digestibility of YPM x Ross 708 male broilers fed diets with varying ME levels and conditioning temperatures from 29 to 42 d of age.

Temperature	Energy	Nutrient Digestibility (%)					AIDE, kcal/kg
		CP	Fat	Calcium	Phosphorus	Potassium	
80°C	Reduced[2]	77.73	88.46	39.72^{a}	50.58	81.42	3,180
	Standard[3]	77.89	92.80	26.04^{bc}	45.81	81.58	3,459
84°C	Reduced	77.38	87.54	33.22^{ab}	50.22	78.88	3,240
	Standard	75.96	92.08	32.64^{abc}	47.76	78.12	3,453
88°C	Reduced	75.85	88.40	25.35^{c}	44.79	79.94	3,210
	Standard	73.57	89.07	27.53^{bc}	41.15	76.14	3,349
SEM[1]		1.40	0.91	1.97	1.90	0.88	35
Main Effects							
80°C		77.81	90.63	32.88^{a}	48.19^{a}	81.50^{a}	3,320
84°C		76.67	89.81	32.93^{a}	48.99^{a}	78.50^{b}	3,347
88°C		74.71	88.73	26.44^{b}	42.97^{b}	78.04^{b}	3,279
SEM		0.94	0.62	1.31	1.22	0.61	24
	Reduced	76.99	88.13^{b}	32.76^{a}	48.53^{a}	80.08^{a}	$3,210^{b}$
	Standard	75.81	91.31^{a}	28.74^{b}	44.90^{b}	78.61^{b}	$3,420^{a}$
SEM		0.75	0.50	1.07	0.97	0.50	19
P-values							
Temperature		0.061	0.094	0.001	0.001	0.003	0.137
Energy		0.264	<.001	0.013	0.009	0.040	<.001
Temperature x Energy		0.650	0.054	0.002	0.785	0.067	0.114

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

[1] SEM= Standard error of the mean

[2] ME levels (kcal/kg) - Starter 3000, Grower 3100, Finisher 3200

[3] ME levels (kcal/kg) - Starter 2870, Grower 2970, Finisher 3070

[4] AIDE = apparent ileal digestible energy (DM basis)

IV. EFFECT OF FEED FORM, ENERGY LEVEL, AND CONDITIONING TEMPERATURE ON BROILER PERFORMANCE, FEED WASTAGE, AND NUTRIENT DIGESTIBILITY FROM 1 TO 21 DAYS OF AGE

ABSTRACT

This experiment evaluated the main effects and interactions of two metabolizable energy (**ME**) levels and three feed forms on broiler performance, feed wastage (**FW**), and nutrient digestibility from 1 to 21 d of age. A total of 648 YPM x Ross 708 male broilers were randomly distributed in 72 battery cages (9 birds/cage) and assigned to six treatments (12 replicates/treatment). Starter diets were formulated to contain two ME levels (2,979 [**E2979**] and 2,875 kcal/kg [**E2875**]). Both diets were fed as mash, crumbles conditioned at 85°C, or crumbles conditioned at 90°C. Body weight gain (**BWG**) and feed intake (**FI**) were determined at 10 and 21 d of age and feed conversion ratio (**FCR**) was adjusted for mortality. On d 10, 15, and 18, the feed spilled was collected from trays placed under each battery cage to calculate FW as g/kg. Ileal digesta (7 birds/cage) was collected for nutrient digestibility analysis on d 21. Data were analyzed as a 2 x 3 factorial arrangement (ME level x feed form) using the GLIMMIX procedure of SAS to evaluate main effects and interactions. Tukey's HSD test was used to separate means and statistical significance was considered at $P \leq 0.05$. Broilers fed E2979 mash and crumbles conditioned at 85°C exhibited higher ($P < 0.05$) BWG from 1 to 10 d, 10 to 21 d, and 1 to 21 d compared to broilers fed E2875 mash and crumbles conditioned at 85°C. However, when broilers were fed crumbles conditioned at 90°C, the ME level of the diet did not influence ($P > 0.05$) BWG in the different evaluated periods. Broilers fed E2979 diets had lower ($P < 0.05$) FCR (1.28 vs. 1.36 g:g) from 1-21 d compared to broilers fed E2875 diets. Additionally, broilers fed mash diets had lower ($P < 0.05$) FI (1049 vs. 1223 and 1215 g) and higher ($P < 0.05$) FCR (1.34 vs. 1.30 and 1.32 g:g)

and FW (28.6 vs. 2.3 and 3.0 g/kg) from 1-21 d compared to broilers fed crumbles conditioned to either 85 or 90°C. The lowest ($P < 0.05$) apparent ileal digestibility (**AID**) of dry matter (**DM**) was observed in broilers fed mash diets with E2875. Broilers fed E2979 diets had improved ($P < 0.05$) AID of crude protein (**CP**) compared to broilers fed E2875 diets. Starch digestibility was lower ($P < 0.05$) in broilers fed crumbles conditioned to 90°C compared to broilers fed crumbles conditioned to 85°C and mash. Overall, broilers responded to both ME level and feed form with the best performance observed when broilers were fed E2979 crumbles conditioned to 85°C.

INTRODUCTION

In broiler production, crumbles are the preferred feed form during the starter period due to their smaller size compared to whole pellets, which makes them easier for small chicks to peck and consume. However, previous researchers have evaluated different feed forms including micro (i.e., 2-3 mm pellets) pellets (Abdollahi et al., 2018a; Rubio et al., 2019), coarse and fine crumbles (Idan et al., 2023), and varying time periods of feeding micro pellets, crumbles, and mash (Rubio et al., 2019; Idan et al., 2020) during the starter period to optimize broiler performance. The benefits of pelleting (e.g., increased feed intake (**FI**), reduced feed wastage (**FW**) and nutrient segregation, and increased resting time) may be more pronounced by keeping the macrostructure of pellets intact (Cerrate et al., 2009). Nonetheless, feeding crumbles provides these benefits with less frequent changes of the pellet die, which is a time-consuming process that may reduce the efficiency of a feed mill as pellet mill capacity drops significantly with smaller pellet diameters. In addition, pellet diameter is negligible since whole pellets will undergo further breaking during the crumbling process.

Another relevant consideration when feeding crumbles is the conditioning temperature used in the pelleting process. This temperature is regulated through the addition of steam into the conditioner, which provides heat and moisture (Thomas et al., 1997). During the conditioning process, there is a combined effect of moisture and heat on the physical and chemical properties of feed. According to Svihus and Zimonja (2011), the temperatures achieved during conditioning and pelleting may result in protein denaturation and the unfolding of the three-dimensional structure of proteins. This could lead to improved digestibility due to the inactivation of enzyme inhibitors and the exposure of new sites for enzymatic action (Abdollahi et al., 2013). In addition, there is a degree of starch gelatinization during conditioning as most cereal starches start denaturing at ranges between 50 and 70°C in excess water conditions (Zimonja and Svihus, 2009; Svihus and Zimonja, 2011).

In addition, it is important to consider the interrelationships between feed processing variables and the nutritional value of feed. Energy represents the greatest cost during feed formulation, and research indicates that feeding varying energy levels can significantly influence broiler performance and nutrient digestibility (Moritz et al., 2003; Jahanian and Ashnagar, 2018; Hernandez et al., 2024). Furthermore, research has demonstrated that feed form (Reece et al., 1985; Amerah et al., 2007; Dozier III et al., 2010; Chewning et al., 2012) and conditioning temperatures (Abdollahi et al., 2011; Teixeira Netto et al., 2019; Boltz et al., 2020; Rueda et al., 2022) influence performance variables and nutrient utilization in poultry production. Abdollahi et al. (2018a) evaluated two feed forms (mash and micro pellets) and five nutrient densities with varying metabolizable energy (**ME**) and lysine levels from 1 to 21 d of age. The authors reported that broilers fed pellets exhibited enhanced performance compared to broilers fed mash across all nutrient density levels. Additionally, the benefits of pelleting were more pronounced at the lowest nutrient density.

However, there is limited research on the interactions between ME levels and feed form during the starter period. Therefore, the objective of this study was to evaluate the main effects and interactions of two ME levels and three feed forms on broiler performance, FW, and nutrient digestibility from 1 to 21 days of age.

MATERIALS AND METHODS

Animal care

This broiler trial was conducted at the Auburn University Charles C. Miller, Jr. Poultry Research and Education Center. All procedures involving the use of live birds were reviewed and approved by Auburn University Institutional Animal Care and Use Committee (PRN 2023-5288).

Bird husbandry

A total of 648-day-old YPM x Ross 708 male broiler chicks (Aviagen North America, Huntsville, AL) were obtained from a commercial hatchery and randomly distributed in 72 battery cages (9 birds/cage; 0.05 m^2/bird) (Petersime, Gettysburg, OH). The research house had a controlled environment and was equipped with a negative pressure ventilation system, exhaust fans, inlet vents, evaporative cooling pads, forced-air heaters, and a control panel for temperature and ventilation management. Feed and water were provided *ad libitum* using a trough feeder and a nipple drinker line with 2 nipples per battery cage. Chicks were provided with supplemental feeders and drinkers during the first seven days. Photoperiod was set at 23L:1D for the first seven days post hatch, 21L:3D from d 7 to 10, and 20 L:4D for the remainder of the study. House temperature was set at 33°C during placement until d 3, 30°C from 4 to 7 d, 28.8°C from 8 to 14 d, and 26.1°C from 15 to 21 d. Birds and house conditions were checked twice daily, and temperature, relative humidity, and mortality were recorded.

Feed formulation, manufacture, and experimental design

Diets were formulated to contain two ME levels: 2,979 kcal/kg (**E2979**) and 2,875 kcal/kg (**E2875**) as illustrated in Table 1. Both diets were fed either as mash, crumbles conditioned at 85°C, and crumbles conditioned at 90°C for a total of six dietary treatments.

Diets were manufactured at the Auburn University Poultry and Animal Nutrition Center. Whole corn was ground using a hammermill (Model 11.5 x 38, Roskamp Champion, Waterloo, IA) equipped with a 4.76-mm screen. Ground corn (4.55 kg) was used to premix phytase (1,500 FTU/kg) in a countertop mixer (Model A-200, The Hobart Mfg. Co., Troy, OH) to ensure a homogenous distribution in the whole batch of feed. Dry ingredients were mixed in a twin shaft mixer (Model 726, Scott Equipment Co, New Prague, MN) using a dry cycle (30 seconds) followed by a wet cycle (120 seconds) after the addition of liquid ingredients. After mixing, diets fed in mash form were bagged. For crumbled diets, mash was conditioned at either 85 or 90°C with 40 seconds retention time and pelleted through a 4.0-mm pellet die (Model 1112-4, California Pellet Mill Co., Crawfordsville, IN). To ensure that all diets were conditioned at the selected temperature, the transition between the pellet mill and cooler was closed until pellets reached the target temperature. Conditioning temperatures were monitored with the computer controller, which indicated the readings obtained by thermometers placed inside the conditioner. Once the target temperature was reached, the transition to the cooler was opened, allowing pellets to be cooled and dried with ambient air using a counter-flow pellet cooler (Model CC0909, California Pellet Mill Co., Crawfordsville, IN). Subsequently, pellets were crumbled using a crumbler (Model 624SS, California Pellet Mill Co., Crawfordsville, IN) with manual roll adjustment. The amount of mixer-added fat was maintained constant across all crumbled treatments to maintain similar pellet and crumble quality, regardless of the energy level of the diet. The additional soybean oil needed in the crumbled E2979 diets was added post-pelleting using a mistcoater (Model no. 5TMX, APEC, Lake Odessa, MI). Titanium dioxide (**TiO_2**) was included in the diets as an indigestible marker to assess nutrient digestibility. Each dietary treatment was randomly assigned to 12 replicate battery cages.

Measurements

Birds and feed were weighed at 1, 10, and 21 d of age to determine body weight gain (**BWG**), FI, and feed conversion ratio (**FCR**). On d 10, 15, and 18 FW was collected from the excreta trays under every battery cage and contamination (i.e., feathers and excreta) were removed with a US sieve #4 (4.75 mm). Recovered FW was cumulative from the whole period between collection days. Feed wastage was calculated as grams of feed wasted per kilogram of feed consumed and used to adjust both FI and FCR. In addition, mortality weights were used to adjust FCR. On d 21, seven birds per cage were randomly selected and euthanized by CO_2 asphyxiation, followed by cervical dislocation, to collect ileal digesta and tibia samples. Ileal digesta was collected from 2 cm posterior of Meckel's diverticulum to 2 cm anterior of the ileal-cecal junction by gently flushing the ileal contents with distilled water. The ileal contents of each pen were pooled in sample cups and frozen at -20°C until further analysis. Left tibias were excised from three birds per cage and frozen at -20°C until tibia ash was analyzed.

Tibia ash analysis

Tibia ash was determined on the tibias collected during necropsy. Frozen tibias were thawed at room temperature and cleaned by removing excess tissue and cartilaginous caps. Clean tibias were weighed, broken into smaller pieces, and individually packed with filter cloth. Then, tibias were exposed to sequential extractions for 24 h in 200-proof ethanol followed by 24 h in anhydrous ether using a Soxhlet apparatus (VWR International, Radnor, PA). Water and non-polar lipids were removed with ethanol, whereas anhydrous ether was used to remove polar lipids. After the sequential extractions, tibias were allowed to dry for a minimum of 24 h. Dry tibias were weighed and ashed at 600°C for 12 h in a muffle furnace as described by Hall et al. (2003). Lastly, the weights of ashed tibias were recorded and tibia ash was calculated using the following formula:

$$Tibia\ ash, \% = \frac{Ashed\ tibia\ weight}{Dry\ tibia\ weight} x\ 100$$

Nutrient digestibility analyses

During feed bagging, representative samples were collected at evenly spaced intervals for nutrient digestibility analysis. Ileal digesta samples collected on d 21 were lyophilized in a Virtis Genesis Pilot Lyophilizer (SP Industries, Warminster, PA) and ground using an electric coffee grinder (Capresso 560.4 Infinity, Montvale, NJ) on the finest setting. After grinding, dried ileal digesta and feed samples were sent to a commercial laboratory (Dairy One Forage Laboratory, Ithaca, NY) to be analyzed for dry matter (**DM**), crude protein (**CP**), and starch. A portion of the ileal digesta was retained for determination of TiO_2 concentration (Short et al., 1996). Apparent ileal digestibility (**AID**) of nutrients was calculated using an equation adapted from Stein et al. (2007):

$$Nutrient\ AID, \% = \left[\frac{\left(\frac{Nutrient}{TiO_2}\right)_{diet} - \left(\frac{Nutrient}{TiO_2}\right)_{digesta}}{\left(\frac{Nutrient}{TiO_2}\right)_{diet}}\right] \times 100$$

where $\left(\frac{Nutrient}{TiO_2}\right)$ represents the ratio of every nutrient to TiO_2 in ileal digesta or diet.

Statistical analyses

For this trial, data were analyzed as a 2 x 3 factorial (ME level x feed form) arrangement in a randomized complete block design to evaluate main effects and interactions with cage location (top, middle, and bottom row) as the blocking factor. Individual battery cages were considered as the experimental unit and each treatment was represented by 12 replicates. When applicable, percentage date was arcsine transformed before statistical analysis. Data were analyzed using the GLIMMIX procedure of SAS version 9.4 (SAS Institute Inc., Cary, NC) and means were separated using Tukey's HSD Test with statistical significance being considered at $P \leq 0.05$.

RESULTS AND DISCUSSION

Broiler performance

Broiler performance parameters are shown in Table 2. Significant interactions ($P < 0.05$) between ME level and feed form were observed for BWG throughout the whole grow-out period. Broilers fed mash and crumbles conditioned at 85°C and formulated to contain E2979 exhibited higher ($P < 0.05$) BWG from 1 to 10 d, 10 to 21 d, and 1 to 21 d compared to broilers fed mash and crumbles conditioned at 85°C but formulated with E2875. However, when broilers were fed crumbled diets conditioned at 90°C, the ME level of the diet did not influence ($P > 0.05$) BWG in the different periods evaluated. In addition, when broilers were fed E2875 diets, the conditioning temperature of the crumbles did not affect BWG across all periods. However, for broilers fed E2979 diets, increasing the conditioning temperature from 85 to 90°C reduced cumulative BWG from 1 to 21 d (947 vs. 889 g: $P < 0.05$).

Furthermore, an interaction between ME level and feed form ($P < 0.05$) was observed for FI from 1 to 10 d. Increasing the ME level from E2875 to E2979 numerically reduced the FI from 262 to 257 grams in broilers fed mash diets and from 305 to 294 grams in broilers fed crumbles conditioned at 90°C. However, when broilers were fed crumbles conditioned at 85°C, increasing the ME level from E2875 to E2979 increased FI from 293 to 301 grams. The ME level did not influence FI from 10 to 21 d or from 1 to 21 days ($P > 0.05$). However, broilers fed crumbles conditioned at 85°C and 90°C had higher ($P < 0.05$) FI from 10 to 21 d and from 1 to 21 d compared to broilers fed mash diets. Similar interactions were observed by Abdollahi et al. (2018a) when feeding mash and pelleted diets (2.0 mm pellets from 1-5 d and 3.0 mm pellets from 5-21 d) diets with five nutrient densities (very low – 2,800 kcal/kg, low – 2,900 kcal/kg, medium – 3,000 kcal/kg, high – 3,100 kcal/kg, and very high – 3,200 kcal/kg) from 1 to 21 d of age. The authors reported that broilers fed pellets had improved BWG, FI, and FCR compared to broilers fed mash diets at each nutrient density level, but the benefits of pelleting were more pronounced at the lowest nutrient density. Massuquetto et al. (2020) assessed two feed forms (mash and pellets) and four ME levels (3,040, 3,120, 3,200, and 3,280 kcal/kg) between days 35 and 47. The authors reported that broilers fed the lowest ME level had the lowest BWG. Broilers fed pellets had a higher BWG (1,501 vs 1,337 g) and FI (2,739 vs 2,489 g) compared to broilers fed mash. Furthermore, Reece et al. (1985) observed that feeding broilers with crumbles promoted higher BWG compared to broilers fed mash from 1 to 21 d of age (633 vs 585 g). Previous literature evaluating the effects of feed form during the initial days of the grow out period (i.e., 1-21 d) have not consistently used the exact same feed form. Nonetheless, the positive responses observed with either pellets or crumbles are generally attributed to the benefits of pelleting, particularly an increase in FI which is the major factor driving BWG (Svihus et al., 2004; Abdollahi et al., 2018b).

No interactions ($P > 0.05$) were observed for FCR. However, main effects of ME level and feed form ($P < 0.05$) were observed for FCR in every evaluated period. Broilers fed the E2979 diets had lower ($P < 0.05$) FCR than broilers fed the E2875 diets from 1 to 10 d (1.01 vs. 1.06 g:g), 10 to 21 d (1.40 vs. 1.50 g:g), and from 1 to 21 d (1.28 vs. 1.36 g:g). Furthermore, broilers fed crumbles conditioned to 85°C presented a lower ($P < 0.05$) FCR compared to broilers fed mash from 1 to 10 and 10 to 21 d of age. From 1 to 21 d, feeding crumbled diets improved ($P < 0.05$) FCR irrespective of conditioning temperature. When comparing the FCR of broiler starters fed similar energy levels as those fed in the present study, varying degrees of improvement have been observed in past research, including differences of 6 points (3,000 and 2,900 kcal/kg; Abdollahi et al., 2018a), 3 points (3,000 and 2,870 kcal/kg; Hernandez et al., 2024), and 2 points (3,000 and 2,900 kcal/kg; Jahanian and Ashnagar, 2018).

Furthermore, previous researchers have reported similar observations to those in the current study when evaluating the effects of feed form on FCR from 1 to 21 days of age (Amerah et al., 2007; Xu et al., 2015; Naderinejad et al., 2016; Lv et al., 2016). Xu et al. (2015) observed that broilers fed crumbles had an 8-point improvement in FCR compared to broilers fed mash from 1 to 14 d. Additionally, Lv et al. (2016) reported a 3-point lower FCR from 1 to 21 d when broilers fed crumbles instead of mash. Since FW was collected and factored into calculating FI in the present study, the improvements observed in FCR with crumbles, can be attributed to the other thermal benefits of conditioning and pelleting/crumbling processes. These benefits include reduced selective feeding (Forbes and Covasa, 1995), reduced eating time and increased resting frequency (Jensen et al., 1962; Skinner-Noble et al., 2005), and increased digestibility of some dietary components (Abdollahi et al., 2013).

In the current study, most effects were associated with either feed form (i.e., mash or crumbles) or ME levels, while conditioning temperatures did not have a strong influence on performance parameters. However, it was observed that when conditioning to 90°C, ME level did not influence the response of BWG. This could be related to the damage of heat labile nutrients (Inborr and Bedford, 1994; Loar II et al., 2014; Boltz et al., 2020) and a lower starch digestibility observed in crumbles conditioned to 90°C (Table 4).

Feed wastage

Feed wastage results were calculated as grams of feed wasted for every kilogram of feed consumed (Table 3). No interactions ($P > 0.05$) between ME level and feed form were observed for FW. However, feed form influenced FW ($P < 0.05$) across all evaluated periods. Broilers fed crumbles from both conditioning temperatures wasted less feed compared to broilers fed mash. In addition, the conditioning temperature of crumbles did not influence FW ($P > 0.05$).

One of the well documented benefits of pelleting is the reduction of FW. This is generally attributed to reduced selective feeding and fewer particles falling from the beak of birds due to the larger size of pellets compared to mash diets (Abdollahi et al., 2013). Although this effect may not be as significant when feeding crumbles during the starter phase, crumbling reduces nutrient segregation, sorting behavior, and FW. However, this benefit remains largely supported by qualitative observation and there are limited studies that have quantified the effect of feed form on FW. Serrano et al. (2013) fed broiler diets as mash, crumbles, and pellets from 1 to 25 d. The authors reported that the lowest FW was observed in broilers fed pellets (0 g/broiler/day) compared to broilers fed crumbles (2.5 g/broiler/day) and mash (3.1 g/broiler/day), which were not different from each other. Gadzirayi et al. (2006) calculated the percentage loss of pelleted and mash feed. They observed that broilers fed pellets wasted 5% of the feed received, whereas broilers fed mash wasted 23%. It is worth noting that FW data is useful to adjust FI and provide more accurate performance results. Therefore, battery trials where FW can be recovered provide useful insights into the benefits of pelleting without FW as a confounding factor.

Tibia ash

Tibia ash (Table 4) was not influenced by feed form ($P > 0.05$), but a main effect of ME level was observed ($P < 0.05$). Broilers fed the E2979 diets had lower ($P < 0.05$) tibia ash than broilers fed the E2875 diets by 1.6 percentage points. Previous research evaluating varying dietary energy levels on bone mineralization has provided conflicting results (Leterrier et al., 1998; Venalainen et al., 2006; Hernandez et al., 2024). The results of the present study agree with the findings of Venalainen et al. (2006), who evaluated two ME levels, which had a difference of 240 kcal/kg between the high and low energy diets. In their experiment, broilers fed the high energy diets exhibited lower tibia ash than broilers fed the low energy diets. Hernandez et al. (2024)

reported that broilers fed reduced ME diets (-130 kcal/kg) from 1 to 42 d had lower tibia ash compared to broilers fed standard energy diets.

One of the reasonings behind the reduction of growth rate through modifications such as energy restriction, is to promote better skeletal development and enhance bone quality (Leterrier et al., 1998). This is because the cortical bone of faster-growing birds may exhibit less mineralization and greater porosity (Shim et al., 2012). This could be particularly important during the early phases of the grow-out as there are periods of rapid bone formation (4 to 18 d) and mineralization (4 to 11 d) (Williams et al., 2000). The present study and previous literature (Williams et al., 2004; Venalainen et al., 2006) support this hypothesis. According to Williams et al. (2004), a rapid circumferential expansion in the bone of fast-growing birds is accompanied by increased porosity (i.e., less mineralization). They suggested that this is regulated by growth rate (i.e., diet) and not genetic predisposition as other authors have discussed (Wise, 1970; Leterrier and Nys, 1992).

Nutrient Digestibility

There was an interaction ($P < 0.05$) between ME level and feed form for AID of DM (Table 4). When broilers were fed diets with a lower ME (E2875), broilers fed mash diets exhibited lower ($P < 0.05$) AID of DM compared to broilers fed crumbles conditioned to either 85 or 90°C. However, this effect was not observed with higher ME level diets (E2979), indicating that the influence of feed form on AID of DM varies depending on the ME content of the diet. Massuquetto et al. (2020) did not observe an interaction between ME level and feed form on AID of DM, but reported that both factors independently influenced DM digestibility. They observed that DM digestibility increased with increasing energy levels and that broilers fed mash had a higher AID of DM by 3.88% compared to broilers fed pellets. In contrast, Massuquetto et al. (2018) reported that broilers fed crumbles exhibited an improved DM digestibility compared to broilers fed mash. Serrano et al. (2013) reported that feeding crumbles or mash did not influence total tract apparent retention (**TTAR**) of DM at 6 and 12 d of age, but broilers fed mash had a higher TTAR of DM than broilers fed crumbles at 25 d of age. Naderinejad et al. (2016) observed that feed form (i.e., crumbles and mash) did not influence AID of DM. These opposing results could be related to several factors including differences in diet composition, type of cereal grain, and conditions of the pelleting process (Khalil et al., 2021).

Apparent ileal digestibility of CP was influenced by ME level and feed form ($P < 0.05$) in the current study. Broilers fed the E2979 diets had higher CP digestibility (76.46 vs. 74.32; $P < 0.05$) compared to broilers fed E2875. In addition, CP digestibility was lower (72.72 vs. 76.62 and 76.82%; $P < 0.05$) in broilers fed mash diets compared to broilers fed crumbles conditioned at 85 or 90°C. Researchers have reported that pelleting leads to protein denaturation and improved CP digestibility (Thomas et al., 1998; Massuquetto et al., 2018; Teixeira Netto et al., 2019). Massuquetto et al. (2018) observed that broilers fed crumbles conditioned to 83°C for 80 and 120 seconds had higher CP digestibility than broilers fed mash from 1 to 25 days of age. Abdollahi et al. (2011) reported that feeding pellets led to a higher digestible protein intake compared to feeding mash. The conditioning process during pelleting may improve CP digestibility by inactivating enzyme inhibitors and denaturing proteins, which may expose new sites for enzymatic action (Abdollahi et al., 2013).

A main effect of feed form ($P < 0.05$) was observed for AID of starch. Broilers fed crumbles conditioned to 90°C had lower ($P < 0.05$) starch digestibility than broilers fed crumbles conditioned to 85°C and mash diets. Abdollahi et al. (2014) did not observe any differences in AID of starch between broilers fed mash and re-ground pellets from 1 to 21 days of age. Similarly, Massuquetto et al. (2018) reported that feeding mash diets and crumbles subjected to varying conditioning times did not influence starch digestibility. However, the pelleting process has the potential of influencing the digestibility of the starch fraction of a diet, since it meets the conditions (i.e., presence of water and high temperatures) necessary for starch gelatinization (Lund, 1984; Svihus et al., 2005). Previous authors have suggested that pelleting could be beneficial or detrimental to starch digestibility depending on the conditioning temperature and the ingredients used in the diet (Abdollahi et al., 2010; Teixeira Netto et al., 2019; Abdollahi et al., 2020). Generally, improvements in starch digestibility as a function of increasing conditioning temperature are attributed to a higher solubilization of starch due to the higher amount of steam added during conditioning (Teixeira Netto et al., 2019). On the other hand, negative effects on starch digestibility could be associated with an increased content of resistant starch (**RS**) and higher diet viscosity, which impairs nutrient absorption in the small intestine (Creswell and Bedford, 2006). Abdollahi et al. (2020) observed that broilers fed diets conditioned to 90°C had a 1.3% lower AID of starch compared to broilers fed diets conditioned to 60°C. In this regard, conditioning to high temperatures can lead to improvements in starch gelatinization. However, it may also lead to the formation of RS, which is not susceptible to enzymatic hydrolysis and can be detrimental to starch digestibility (Creswell and Bedford, 2006).

CONCLUSIONS

1. Broilers fed diets with higher energy had improved growth performance and CP digestibility but lower tibia ash.
2. Feeding broilers crumbled diets led to improved performance, reduced FW, and nutrient digestibility.

3. The best performance in terms of BWG was observed in broilers fed the higher energy crumbles conditioned to 85°C.
4. Starch digestibility was reduced when broilers were fed crumbles conditioned to 90°C.

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Table 4. 1 Ingredient and nutrient composition of dietary treatments fed to YPM x Ross 708 male broilers from 1 to 21 d of age.

Ingredient, % as-fed (unless otherwise noted)	Starter, 1 to 21 d	
	E2979[1]	E2875[2]
Corn	40.173	42.441
Soybean meal	39.416	39.114
Wheat middlings	14.205	14.205
Soybean oil - Mixer	0.500	0.500
Soybean oil - PPLA	1.963	–
Calcium carbonate	1.055	1.059
Dicalcium phosphate	0.718	0.715
Salt	0.396	0.396
DL-Methionine	0.370	0.367
L-Lysine	0.207	0.210
L-Threonine	0.128	0.127
L-Valine	0.043	0.041
Trace mineral premix[3]	0.100	0.100
Vitamin premix[4]	0.100	0.100
Choline chloride	0.084	0.082
Quantum Blue®[5], g/kg	0.100	0.100
Titanium dioxide	0.500	0.500
Xylanase	0.004	0.004
Inert filler	0.009	0.009
Calculated nutrients, % as-fed (unless otherwise noted)		
AMEn[6], kcal/kg	2,979	2,875
Crude protein	24.968	25.006
Digestible Lys	1.260	1.260
Digestible TSAA	0.950	0.950
Digestible Thr	0.840	0.840
Digestible Val	0.960	0.960
Digestible Ile	0.840	0.840
Digestible Leu	1.641	1.650
Digestible Arg	1.384	1.382
Digestible Trp	0.252	0.251
Calcium	0.950	0.950
Nonphytate P	0.500	0.500

[1] Metabolizable energy level - 2,875 kcal/kg

[2] Metabolizable energy level - 2,979 kcal/kg

[3] Mineral premix includes 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 (ethylenediaminedihydroxide), 1.4 mg; and Se (sodium selenite), 0.3 mg.

[4] Vitamin premix includes per kg of diet: Vitamin A (Vitamin A acetate), starter: 18,740 IU, grower: 14,992 IU, finisher 9,370 IU; Vitamin D (cholecalciferol), starter: 6,614 IU, grower: 5,291 IU, finisher: 3,307 IU; Vitamin E (DL-alpha tocopherol acetate), starter: 78 IU, grower: 66 IU, finisher: 47 IU; menadione (menadione sodium bisulfate complex), starter: 4 mg, grower: 3 mg, finisher: 2 mg; Vitamin B12 (cyanocobalamin), starter: 0.03 mg, grower: 0.03 mg, finisher: 0.02 mg; folacin (folic acid), starter: 4.14 mg, grower: 3.44 mg, finisher 2.55 mg; D-pantothenic acid (calcium pantothenate), starter: 39 mg, grower: 32 mg, finisher: 23 mg; riboflavin (riboflavin), starter: 24 mg, grower: 19 mg, finisher: 13 mg; niacin (niacinamide), starter: 108 mg, grower: 90 mg, finisher: 63 mg; thiamin (thiamine mononitrate), starter: 8.3 mg, grower: 7.2 mg, finisher: 5.6 mg; D-biotin (biotin), starter: 0.33 mg, grower: 0.28 mg, finisher: 0.22 mg, and pyridoxine (pyridoxine hydrochloride), starter: 14 mg, grower: 13 mg, finisher: 10 mg.

[5] Quantum Blue® (AB Vista, Marlborough, Wiltshire, UK) provides 1,500 FTU/kg of phytase activity per kg of diet.

[6] AMEn values account for 100 kcal/kg of energy contributed by xylanase and phytase.

Table 4. 2 Growth performance of YPM x Ross 708 male broilers fed diets with varying ME levels and feed form from 1 to 21 d of age.

Energy	Feed Form	Body Weight Gain (g)			Feed Intake (g)			FCR (g:g)		
		Days of Age								
		1 to 10	10 to 21	1 to 21	1 to 10	10 to 21	1 to 21	1 to 10	10 to 21	1 to 21
E2875[1]	Mash	195^{d}	502^{d}	700^{d}	262^{b}	777	1038	1.07	1.53	1.38
	Crumble 85°C	240^{b}	605^{bc}	846^{b}	293^{a}	905	1201	1.05	1.48	1.34
	Crumble 90°C	245^{b}	628^{b}	882^{b}	305^{a}	921	1224	1.05	1.49	1.35
E2979[2]	Mash	212^{c}	563^{c}	767^{c}	257^{b}	795	1060	1.02	1.42	1.30
	Crumble 85°C	259^{a}	681^{a}	947^{a}	301^{a}	939	1245	1.00	1.38	1.26
	Crumble 90°C	248^{ab}	643^{ab}	889^{b}	294^{a}	908	1205	1.02	1.41	1.29
SEM[3]		3	11	13	3	14	16	0.008	0.017	0.011
Main Effects										
E2875		227^{b}	578^{b}	809^{b}	287	868	1154	1.06^{a}	1.50^{a}	1.36^{a}
E2979		240^{a}	629^{a}	868^{a}	284	881	1170	1.01^{b}	1.40^{b}	1.28^{b}
SEM		2	6	7	2	8	9	0.004	0.01	0.01
	Mash	203^{b}	532^{b}	734^{b}	260^{b}	786^{b}	1049^{b}	1.05^{a}	1.47^{a}	1.34^{a}
	Crumble 85°C	249^{a}	643^{a}	896^{a}	297^{a}	922^{a}	1223^{a}	1.02^{b}	1.43^{b}	1.30^{b}
	Crumble 90°C	247^{a}	635^{a}	886^{a}	299^{a}	915^{a}	1215^{a}	1.04^{ab}	1.45^{ab}	1.32^{b}
SEM		2	8	9	2	9	11	0.006	0.012	0.007
P-values										
Energy		<.001	<.001	<.001	0.311	0.239	0.202	<.001	<.001	<.001
Feed Form		<.001	<.001	<.001	<.001	<.001	<.001	0.006	0.033	0.001
Energy x Feed Form		0.042	0.018	0.002	0.007	0.206	0.115	0.269	0.843	0.479

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

[1]Metabolizable energy level - 2,875 kcal/kg

[2]Metabolizable energy level - 2,979 kcal/kg

[3]SEM= Standard error of the mean

Table 4. 3 Feed wastage of YPM x Ross 708 male broilers fed diets with varying ME levels and feed form from 1 to 21 d of age.

Energy	Feed Form	Feed Wastage (g/kg)[4] Days of Age 1 to 10	 10 to 21	 1 to 21
E2875[1]	Mash	26.5	28.5	29.4
	Crumble 85°C	3.9	1.7	2.3
	Crumble 90°C	3.6	2.8	3.7
E2979[2]	Mash	36.7	24.9	27.9
	Crumble 85°C	4.1	1.6	2.4
	Crumble 90°C	3.7	1.7	2.3
SEM[3]		3.4	3.0	2.9
Main Effects				
E2875		11.3	11.0	11.8
E2979		14.8	9.4	10.9
SEM		1.9	1.7	1.6
	Mash	31.6^{a}	26.7^{a}	28.6^{a}
	Crumble 85°C	4.0^{b}	1.6^{b}	2.3^{b}
	Crumble 90°C	3.6^{b}	2.2^{b}	3.0^{b}
SEM		2.3	2.1	2.0
	P-values			
Energy		0.195	0.489	0.678
Feed Form		<.001	<.001	<.001
Energy x Feed Form		0.213	0.823	0.947

[a-b]Least square means within a column with different superscripts differ significantly (*P ≤ 0.05*)

[1]Metabolizable energy level - 2,875 kcal/kg

[2]Metabolizable energy level - 2,979 kcal/kg

[3]SEM= Standard error of the mean

[4]Feed wastage was calculated as grams of feed wasted per kilogram of feed consumed

Table 4. 4 Apparent ileal nutrient digestibility and tibia ash of YPM x Ross 708 male broilers fed diets with varying ME levels and feed form from 1 to 21 d of age.

Energy	Feed Form	Tibia Ash (%)	Nutrient Digestibility (%)		
			Dry Matter	Crude Protein	Starch
E2875[1]	Mash	57.4	57.68^{b}	70.29	98.18
	Crumble 85°C	57.4	64.91^{a}	76.17	97.84
	Crumble 90°C	56.9	63.88^{a}	76.49	97.20
E2979[2]	Mash	55.5	62.71^{a}	75.16	98.22
	Crumble 85°C	56.9	65.47^{a}	77.07	97.50
	Crumble 90°C	54.5	64.24^{a}	77.15	96.84
SEM[3]		0.7	1.04	1.20	0.23
Main Effects					
E2875		57.2^{a}	62.16^{b}	74.32^{b}	97.74
E2979		55.6^{b}	64.14^{a}	76.46^{a}	97.52
SEM		0.4	0.58	0.65	0.13
	Mash	56.4	60.20^{b}	72.72^{b}	98.20^{a}
	Crumble 85°C	57.1	65.19^{a}	76.62^{a}	97.67^{a}
	Crumble 90°C	55.7	64.06^{a}	76.82^{a}	97.02^{b}
SEM		0.7	0.72	0.81	0.16
			P-values		
Energy		0.005	0.020	0.023	0.215
Feed Form		0.105	<.0001	0.0004	<.0001
Energy x Feed Form		0.320	0.039	0.122	0.571

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

[1] Metabolizable energy level - 2,875 kcal/kg

[2] Metabolizable energy level - 2,979 kcal/kg

[3] SEM= Standard error of the mean

V. CONCLUSIONS

The physiological response of birds to feed is dependent on several factors, including feed processing variables and the inherent nutritional characteristics of feed. These two variables are often considered separately, but they are closely related and may interact to influence broiler performance and nutrient utilization. For instance, feed form and the temperatures used during the conditioning process may influence the nutritional value of feed. Therefore, decisions made at the feed mill play an important role in determining the characteristics of the finished feed and how birds respond to it. Since birds should receive the feed formulated by the nutritionist, every variable in feed processing that affects their response should be carefully analyzed.

Due to limited research evaluating the interactions between feed processing parameters and metabolizable energy (**ME**) levels, two experiments were designed to evaluate the influence of these variables on broiler performance and nutrient utilization. Experiment 1 evaluated diets formulated with two ME levels (standard energy (**SE**) and -130 kcal/kg reduced energy (**RE**). These diets were manufactured using three conditioning temperatures: 80, 84, and 88°C. Broilers were fed six dietary treatments to evaluate performance, processing yield, footpad lesions, tibia ash, and nutrient digestibility from 1 to 42 d of age. Conditioning temperatures influenced pellet quality with diets conditioned to 88°C having the highest pellet durability index (**PDI**) in both the grower and finisher phases. However, most performance and processing parameters were unaffected by conditioning temperatures. Broilers fed SE diets showed improved growth performance, tibia ash, apparent ileal digestibility (**AID**) of fat and energy, and a lower incidence of footpad lesions. In addition, breast yield was higher in broilers fed RE diets, likely due to higher amino acid intake. Lastly, it was observed that increasing conditioning temperatures led to reduced mineral digestibility.

A second experiment was designed to evaluate the impact of two ME levels and three feed forms on broiler performance, feed wastage (**FW**), and nutrient digestibility from 1 to 21 d of age. The energy levels of the starter diets were 2,979 (**E2979**) and 2,875 kcal/kg (**E2875**) and both diets were fed as mash, crumbles conditioned at 85°C, and crumbles conditioned at 90°C, resulting in six dietary treatments. The influence of feed form on body weight gain (**BWG**) and AID of dry matter (**DM**) was dependent on the ME level of the diet. When broilers were fed crumbles conditioned to 90°C, the ME level of the diet did not influence BWG in the different evaluated periods, contrasting with broilers fed mash and crumbles conditioned to 85°C. In addition, the lowest DM digestibility was observed in broilers fed mash diets with E2875. Overall, broilers fed higher energy diets exhibited improved growth performance and AID of crude protein (**CP**). Similarly, broilers fed crumbled diets showed improved performance, reduced FW, and higher nutrient digestibility. The benefit of reduced FW when feeding broilers pelleted or crumbled diets remains largely supported by unquantified observation, so these results emphasize the importance of pelleting to enhance broiler performance.

Overall, both experiments support previous literature demonstrating the benefits of pelleting on broiler performance and nutrient digestibility. However, the results indicate that the response of broilers to pelleted diets varies depending on several feed processing and nutritional variables. For example, the response of birds to feed form may be dependent on the nutrient density of the diet. Additionally, some practices commonly used to improve pellet quality may be detrimental to broiler performance and nutrient utilization. Therefore, the interrelationships between these variables should be considered to achieve the goal of manufacturing high quality feed without compromising nutrient availability.