Final Report

for

United Sorghum Checkoff Program (USCP)

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Executive Summary

Sorghum has not enjoyed the penetration of the Southeastern U.S. feedstuffs market that corn has experienced for decades. Early research with sorghum in broiler diets indicated that birds did not grow as well on grain sorghum as a corn-based diet due to the presence of antinutritional factors. Recent genetic improvements in grain sorghum have reduced tannin levels to essentially zero, and utilization of phytases has helped remove the negative effects of phytates in sorghum and other grains. However, there are limited data concerning the nutritional value of the new modern grain sorghum varieties to gain wide acceptance of the grain as a full replacement for corn in broiler diets. Also, research concerning the grain sorghum's nutritional value in support of growing gamebirds is practically nonexistent.

Controlled research studies showing both the nutritional value and the impact on growth, health, and product quality on a variety of poultry species are needed. Further, this information must be provided to poultry integrators coupled with economic analyses showing producers how to best utilize grain sorghum as an additional resource for their operations. The objectives of this work were to determine the nitrogen-corrected apparent metabolizable energy (AME_n) of different grain sorghum varieties/products (red/bronze, white/tan, and yellow No.2) in three poultry species: broiler chickens, Japanese quail, and bobwhite quail. Also, AME_n values obtained for broiler chickens and Japanese quail were validated in grow-out studies.

The mean AME_n values of modern grain sorghum varieties for broilers in the grower diet-phase were determined as 3,326 (red/bronze), 3,288 (white/tan), and 2,546 (U.S. No. 2 Yellow) kcal/kg, respectively. In the finisher diet-phase, average AME_n values were determined as 3,409 (red/bronze), 3,535 (white/tan), and 3,736 (U.S. No. 2 Yellow) kcal/kg, respectively. AME_n determination for broilers indicates that modern grain sorghum varieties showed potential for replacing corn in diet formulation without sacrificing important performance factors, including bodyweight (B.W.), feed intake (F.I.), and feed conversion ratio (FCR).

Mean AME_n values of modern grain sorghum varieties for Bobwhite quail at 6-weeks of age were determined as 3,610 (red/bronze), 3,544 (white/tan), and 3,577 (U.S. No. 2 Yellow) kcal/kg. At 11-weeks of age, the determined AME_n values were 3,311 (red/bronze), 3,297 (white/tan), and 2,497 (U.S. No. 2 Yellow) kcal/kg. No significant differences were observed in the AME value and 96-hr F.I. at 6 and 11-weeks of age. No significant differences were observed in BW, FI, or FCR at 6 and 11 weeks of age.

Mean AME_n values of modern grain sorghum varieties for Japanese quail at 3-weeks of age were determined as 3,524 (red/bronze), 3,252 (white/tan), and 3,039 (U.S. No. 2 Yellow) kcal/kg, respectively. At 6-weeks of age, average AME_n values were determined as 3,373 (red/bronze), 3,279 (white/tan), and 2,966 (U.S. No. 2 Yellow) kcal/kg, respectively.

Broiler growth performance trials indicated that modern grain sorghum varieties show potential for replacing corn at full substitution in diet formulation without negatively affecting FCR as well as carcass traits, including carcass yield, breast weight, and breast yield. Benefit-cost ratio (BCR) analysis revealed that the corn diet has the highest BCR and the second highest BCR for broilers belongs to the red/bronze-based diet.

Growth performance trials for Japanese quail indicated that modern grain sorghum varieties showed potential for replacing corn at full substitution in diet formulation without negatively affecting performance factors, including B.W., F.I., FCR, and the carcass traits of hot carcass weight, carcass yield, breast weight and breast yield. The inclusion level of grain sorghum in diet formulation will be dependent on cost and availability of grain. BCR analysis showed that corn-based diet had the highest BCR, followed by red/bronze sorghum, assuming that cost of 1lb of corn and any variety of sorghum were \$0.12 and \$0.14, respectively. However, when the cost of sorghum was the same as corn,

red/bronze-based diet becomes the most cost-effective diet for Japanese quail producers.

Most of the existing nutrient composition and performance data for grain sorghum fed to poultry are inconsistent and focused on high tannin varieties and their negative influence on poultry. Data from this project provides nutritionists with an updated nutrient composition of tannin-free grain sorghum, an initial benefit-cost ratio analysis and provides a step forward in giving producers confidence in using modern varieties of grain sorghum in commercial poultry production.

Technical Objectives

Goal: Enhance the marketing opportunities for grain sorghum varieties through a better understanding of the nutritional and economic benefits for use in poultry and game bird production enterprises

Determine the apparent metabolizable energy (AME) value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding commercial broilers to target weight

Objective 2: Determine the AME value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding bobwhite quail to target weight/age

Objective 3: Determine the AME value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding Japanese quail to target weight/age

Objective 4: Determine the growth rates and economic impact of commercial broilers fed selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum in relation to that of a standard corn based diet

Objective 5 : Determine the growth rates and economic impact of bobwhite quail fed selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum in relation to that of a standard corn based diet *(Note: After discussion with the USCP, this objective was eliminated from the project. The funds were rellocated to repeat the broiler growout trial proposed for Objective 4)*

Objective 6: Determine the growth rates and economic impact of Japanese quail fed selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum in relation to that of a standard corn based diet

Background

By 2050, it is estimated that the human population will reach 9 billion with a concomitant increase in food demand[1]. Contributing to this increase in food demand is not only the increase in population, but also an increase in affluence of world populations. The increases in affluence and population are not only increasing demand for more crop production, but also an increase in demand for high quality animal products (predicted to grow faster than crops) in the form of meat, poultry, fish, milk, eggs, leather and fiber[2]. To meet this demand will require a 70% increase in food production. This increase will have to come with no additional land resources and in the face of climate change, soil loss, pest and pathogen damage as well as potable water availability issues. Using today's technology and capacity to increase production to these levels would require nearly 1 billion more hectares of farm land (nearly the size of Canada)[1], without consideration of the other factors mentioned above. No such available land resources exist. Thus, research will be needed to substantially increase the efficiency of production (both crop and animal).

Grain sorghum, a cereal crop well adapted to the environment of much of the Southeastern (S.E.) United States (U.S.), is much more tolerant of heat, drought and lower soil fertility than corn, the primary grain crop in the U.S., making it a superior grain crop selection for marginal croplands and highly variable climates[3]. However, sorghum has not enjoyed the penetration of the S.E. U.S. feedstuffs market (driven heavily by the poultry industry) that corn has experienced as it remains the second most used cereal grain for poultry and egg production[4]. Early research (1950's to early 1990's) with sorghum in broiler diets indicated that birds did not grow as well on grain sorghum as a corn based diet. Subsequent research indicated that tannins, phytates and karifin compounds were responsible for reduced protein digestibility[5] and growth performance of birds consuming grain sorghum[6]. Recent genetic improvements in grain sorghums have reduce tannin levels to essentially zero and utilization of phytases has helped remove the negative effects of phytates in sorghum and other grains[6]. However, there is limited data concerning the nutritional value of the new modern grain sorghum varieties to gain wide acceptance of the grain as a full replacement for corn in broiler diets and research concerning the of grain sorghum's nutritional value in support of growing gamebirds is practically nonexistent, a growing market opportunity for the grain industry.

The National Chicken Council reports that the broiler industry as a whole utilizes >1.2 billion bushels of corn for production each year[7]. This utilization of corn for the broiler industry is approximately twice the number of bushels of sorghum produced in the U.S. annually (world's largest sorghum producer), as reported by the United Sorghum Checkoff Program (USCP)[8]. Most sorghum production in the U.S. appears to be located primarily west of the Mississippi river, whereas the broiler industry is located primarily from Mississippi east with 8 of the top 10 broiler producing states located in the S.E. U.S[7]. Further quail production is largely located in the south with an annual production of >6 million birds[9]. (*Manchester Farms is located in South Carolina and is one of the 4 largest quail producers in the world*; *see attached email of support for this proposal*). The thriving Plantation gamebird industry in the south utilizes significant quail numbers for their operations as well. Given that much of the land in the S.E. U.S. is generally less fertile than that of the plains states and corn belt and given that sorghum is a crop that tolerates lower soil fertility and wide climate swings (especially with regards to drought and heat, two real issues in the S.E.), sorghum is a near perfect crop to grow in the south near a large epicenter of poultry (including quail) production. Further, the reported nutritional equivalency (though data is limited, especially with regards to quail) of the crop to corn of the new modern varieties of grain sorghum indicate it could be an ideal grain for poultry production in the SE[4].

Having the crop grown close to the markets of utilization reduces transport costs and provides local grain farmers more options for sustainability of their operations. However, for increased grain sorghum production and utilization to occur in the S.E., the continued perception of the grain's past negative effects on poultry production must be overcome. For that to happen, controlled research studies showing both the nutritional value and the impact on growth, health, and product quality of a variety of poultry species are needed. Further, this information must be provided to poultry producers coupled with economic analyses showing the producers how to best utilize grain sorghum as an additional resource for their operations. The USCP has the mission "*to increase producer profitability and enhance the sorghum industry*". In support of the USCP mission, our research group established a goal and objectives toward enhancing utilization of grain sorghum in production bird operations (gamebird and broiler markets).

To address the technical objectives described in the previous section, our team conducted six experiments using three production bird species to evaluate three selected varieties of modern sorghum for use in production enterprises.

Objective 1. Determine the apparent metabolizable energy (AME) value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding commercial broilers to target weight

Materials and methods
All procedures were approved by the Clemson University Institutional Animal Care and Use Committee (AUP #2017-051).
Birds and husbandry. Two trials with identical procedures were conducted for a 1-47 days of age grow-out period. Trials evaluated the AME_n response of 224 mixed-sex Cobb 500 x Hubbard commercial

broilers from 22 to 24 days of age and 43 to 45 days of age. At 1 day-of-age, birds were housed in a solid-sided research house and randomly distributed (4 birds per cage) in heated battery brooder cages, 34 cm x 98 cm, and transferred at 21 days of age to grower battery cages, 61 cm x 71 cm (Petersime, Zulte, Belgium). Each grower battery cage was provided with a metal trough feeder and water unit. In both trials, the temperature of the cage was 35ºC at placement and gradually decreased to reach 27ºC and following a lighting program of 16 hours of light to 8 hours of dark (16L:8D) throughout the study.

Tannin analysis. Varieties of grain sorghum used in this experiment were analyzed for tannin content to ensure zero tannin content before use in experimental diets. An acid-butanol assay (University of Miami, Oxford, OH) for proanthocyanidins was conducted on red/bronze, white/tan, and the U.S. No. 2 yellow grain sorghum varieties. In this assay, acid was added to a sample of each grain to yield a colored product, (known as cyaniding) or a colorless product, (known as catechin) if tannins were present or absent, respectively (Hagerman, 2002). The colored product has an absorbance peak at 550 nm and is characteristic of a high tannin grain (Hagerman, 2002). The absorbance measured for each grain sorghum variety for this experiment yielded no product at 550 nm compared to the pure sorghum with spectra at 550 nm (Figure 1.a.); thus, no tannins were present in the varieties used for this experiment. Additional confirmation for the presence of tannins in the red/bronze variety, which is more commonly known to contain higher tannin content, was tested at a high and low concentration of tannin to ensure that there were no traces of tannins in larger sample sizes. Results showed similar spectra for both concentrations with no peak at 550nm, indicating no tannin traces in any of the samples (Figure 1.b.).

Experimental treatments. Three modern varieties of grain sorghum commonly grown in the southeastern U.S., red/bronze, white/tan, and U.S. No. 2 Yellow were obtained from the states of Florida and North Carolina and used for all poultry diets. All diets were fed mash feed ad-libitum and formulated based on an industry-standard supplied by a commercial nutritionist. All birds were fed a corn-based acclimation diet on days 1-3. On day 4, birds were randomly assigned 1 of 4 corn-soybean meal basal diets comprised of 80% of the energy from the corn-soybean meal basal and completed with 20% of the energy from the grain sorghum (red/bronze, white/tan, or U.S. No. 2 Yellow) for treatment diets or dextrose for the control diet. The basal diet was based on removing 20% of the gross energy of corn and replacing the appropriate amount of grain sorghum variety or dextrose with each of their respective analyzed nutrient and gross energy values for treatment and control diets (Table A1). All whole grain sorghum was ground through a hammer mill (Premier 1 Supplies, Washington, Iowa) with a 4-mm sieve. Both broiler trials included 8 cages for the control diet, and 16 cages (replicates) per treatment for each of the 3 grain sorghum variety treatments. The ingredient compositions, nutrient, and gross energy analyses for basal and treatment diets are shown in Tables A2, A3, A4, and A5.

Excreta collection and measurements. Excreta collection and other measurements for AME_n determination of grain sorghum was determined in the grower and finisher diet phases for broilers from 22 to 24 days and 43 to 45 days of age during a 72-hr total excreta collection period. At the end of each collection period, feed disappearance and total excreta weight were measured. A 30-g sample of feed and excreta was analyzed for dry matter, gross energy, and nitrogen content with a bomb calorimeter and combustion N analyzer at the University of Georgia Feed, Environmental and Water (FEW) Laboratory (Athens, Georgia). F.I., excreta weight, gross energy (G.E.), and nitrogen content results were used to calculate the nitrogen corrected AME_n of grain sorghum using the difference method by MacLeod et al. (Macleod et al., 2008):

(1) ***Treatment AME:*** $AME_n = [GEI - GEE] - [8.73 \times (NI - NE)] \div FI$

(2) ***Sorghum AME:*** $AME_{grain\ sorghum} = AME_{basal} + (AME_{treatment} - AME_{basal}) \div$ (proportion of added grain sorghum)

where GEI = gross energy intake; GEE = gross energy output in excreta; NI = nitrogen intake from the diet; NE = nitrogen output from excreta; FI = feed intake; and 8.73 = nitrogen correction factor from previous research (Titus et al., 1959).

Birds were group weighed (kg/cage), and feed disappearance was measured weekly on days 1, 8, 15, 22, 29, 36, 43, and 47. Weekly measures of group body weight (B.W.) and feed disappearance were used to calculate F.I. (15-22 days of age and 36-43 days of age) and feed conversion ratio (FCR) per treatment. Mortality was recorded daily to adjust for body weight and feed intake of birds that died over the grow-out periods.

Statistical analyses. Data were analyzed as a randomized complete block design with the two trials as the blocking factor. Statistical analyses for feed, excreta, body weight, AME_n, and 72-hour feed intake were performed separately for the grower and finisher-diet phases. The analyses were based on a linear model with a fixed effect of treatment and random effect of block. The model effects were assessed with ANOVA, and Fisher's Least Significant Difference procedure was performed to determine specific differences between treatment means. P-values $\leq$ 0.05 were considered evidence of statistical significance. All statistical calculations were performed using JMP Pro version 15.2.0 (SAS Institute Inc., Cary, NC).

Objective 2. Determine the AME value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding bobwhite quail to target weight/age

Materials and Methods

All procedures were approved by the Clemson University Institutional Animal Care and Use Committee (AUP #2017-051).

Birds and Husbandry. Two trials with identical procedures were conducted for a 1 to 84 day of age grow-out period. Trials evaluated the AME_n response of 230 mixed-sex Bobwhite quail at 6-weeks of age (41 to 44 days) and 11-weeks of age (79 to 82 days). In each trial, quail were housed in a solid-sided research house and randomly distributed (5 birds per cage) in heated battery brooder cages, 34 cm x 98 cm (Petersime, Zulte, Belgium). Each starter battery cage was provided with a trough feeder and quart jar waterer. In both trials, the temperature of the house was 37ºC at placement and gradually decreased to reach 27ºC with 16 hours of light to 8 hours of dark (16L:8D) throughout the study.

Tannin analysis. *See Objective 1. Tannin analysis*

Treatments. Three modern varieties of grain sorghum commonly grown in the southeastern U.S., red/bronze, white/tan, and U.S. No. 2 Yellow, were obtained from Florida and North Carolina and used for all diets. The red/bronze and white/tan grain sorghum varieties were identity preserved, while U.S. No. 2 yellow was a red/bronze based variety that may have contained other mixed grain sorghum varieties. All whole grain sorghum was ground through a hammer mill (Premier 1 Supplies, Washington, Iowa) with a 4-mm sieve.

Bobwhite quail were fed starter/grower mash feed ad-libitum and formulated based on an industry standard supplied by a commercial nutritionist. All birds were fed a corn-based acclimation diet on days 1 to 3. On day 4, birds were randomly assigned 1 of 4 corn basal diets with 20% of the calories for the gross energy (GE) of corn replaced by the equivalent calories of the respective GE of grain sorghum (red/bronze, white/tan, or U.S. No. 2 Yellow) or dextrose for the control, corn/dextrose diet. Dextrose was used as a reference ingredient due to its known energy content that would replace 20% of the calories for the GE of corn removed for the corn/dextrose diet. The classical basal substitution method (Sibbald et al., 1960) was adapted in this study to formulate treatment diets based on the GE content of corn to be replaced with an energetically equivalent amount of grain sorghum to target a more practical approach and evaluation for future use by commercial nutritionists. The ingredient composition, nutrient analyses, and AME_n for the basal and complete test diets are shown in Tables 6A and 7A. Both trials included 10 replicates of treatment diets over the grow-out of 1 to 84 days of age.

Excreta collection and measurements. Excreta collection and other measurements for AME_n determination of grain sorghum was determined in Japanese quail at 6-weeks of age (41 to 44 days) and 11-weeks of age (79 to 82 days). At the end of each collection period, feed disappearance and total excreta weight were measured. A 30-g sample of feed and excreta was analyzed for dry matter, GE, and nitrogen content with a bomb calorimeter and combustion N analyzer at the University of Georgia Feed, Environmental and Water (FEW) Laboratory (Athens, Georgia). Feed intake (FI), excreta weight, GE, and nitrogen (N) content results were used to calculate the nitrogen corrected AME_n of grain sorghum using the difference method by MacLeod et al. (Macleod et al., 2008):

(1) ***Treatment AME_n:*** $AME_n = [GEI - GEE] - [8.73 \times (NI - NE)] \div FI$

(2) ***Sorghum AME_n:*** $AME_{n\ \text{grain sorghum}} = AME_{n\ \text{basal}} + (AME_{n\ \text{treatment}} - AME_{n\ \text{basal}}) \div$ (proportion of added grain sorghum)

where GEI = gross energy intake; GEE = gross energy output in excreta; NI = nitrogen intake from the diet; NE = nitrogen output from excreta; FI = feed intake; and 8.73 = nitrogen correction factor from previous research (Titus et al., 1959).

Birds were group weighed (kg/cage), and feed disappearance was measured weekly on days 1, 8, 15, 22, 29, 36, 43, 50, 57, 64, 71, 78 and 84. Mortality was recorded daily for birds that died over the grow-out period. Weekly measures of group body weight (BW) and feed disappearance were used to calculate FI (6-weeks of age and 11-weeks of age) and feed conversion ratio (FCR) per treatment:

Statistical Analyses. The initial analyses were based on a 2 x 4 factorial treatment design with age (6-weeks and 11-weeks) and grain types (corn/dextrose, red/bronze, white/tan, and U.S. No.2 yellow) defining the treatments, and a randomized complete block experiment design with cage and trials defining the block. The model effects were assessed with ANOVA based on the treatment and experiment designs. No significant evidence was observed for an age and grain type interaction for many of the response variables; therefore, analyses of grain type effects were performed separately for the two ages. Fisher's Least Significant Difference procedure was used to determine specific differences among the grain type means. P-values $\leq$ 0.05 were considered evidence of statistical significance. All statistical calculations were performed using JMP Pro version 15.2.0 (SAS Institute Inc., Cary, NC).

Objective 3. Determine the AME value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding Japanese quail to target weight/age

Materials and Methods

All procedures were approved by the Clemson University Institutional Animal Care and Use Committee (AUP #2017-051).

Birds and Husbandry. Two trials with identical procedures were conducted for a 1 to 40 day of age grow-out period. Trials evaluated the AME_n response of 314 mixed-sex commercial Japanese quail (*Coturnix japonica*) at 3-weeks of age (19 to 21 days) and 6-weeks of age (36 to 38 days). In each trial, 157 quail were housed in a solid-sided research house and randomly distributed (5 birds per cage) in heated battery brooder cages, 34 cm x 98 cm (Petersime, Zulte, Belgium). Each starter battery cage was provided with a trough feeder and quart jar waterer. In both trials, the temperature of the house was 37ºC at placement and gradually decreased to reach 27ºC with 16 hours of light to 8 hours of dark (16L:8D) throughout the study.

Tannin analysis. *See Objective 1. Tannin analysis*

Treatments. Three modern varieties of grain sorghum commonly grown in the southeastern U.S., red/bronze, white/tan, and U.S. No. 2 Yellow, were obtained from Florida and North Carolina and used for all diet. The red/bronze and white/tan grain sorghum varieties were identity preserved, while U.S. No. 2 yellow was a red/bronze based variety that may have contained other mixed grain sorghum varieties. Nutrient and gross energy (G.E.) analyses of grain sorghum used in the experimental diets are shown in Table A8. All whole grain sorghum was ground through a hammer mill (Premier 1 Supplies, Washington, Iowa) with a 4-mm sieve. Japanese quail were fed starter/grower mash feed ad-libitum and formulated based on an industry standard supplied by a commercial nutritionist. All birds were fed a corn-based acclimation diet on days 1 to 3. On day 4, birds were randomly assigned 1 of 4 corn basal diets with 20% of the calories for the gross energy (G.E.) of corn replaced by the equivalent calories of the respective G.E. of grain sorghum (red/bronze, white/tan, or U.S. No. 2 Yellow; Table A8) or dextrose for the control, corn/dextrose diet. Dextrose was used as a reference ingredient due to its known energy content that would replace 20% of the calories for the G.E. of corn removed for the corn/dextrose diet. The classical basal substitution method (Sibbald et al., 1960) was adapted in this study to formulate treatment diets based on the G.E. content of corn to be replaced with an energetically equivalent amount of grain sorghum to target a more practical approach and evaluation for future use by commercial nutritionists. The ingredient composition, nutrient analyses, and AME_n for the basal and complete test diets are shown in Tables A9 and A10. Both Japanese quail trials included 10 replicates of control diet, and each of the three grain sorghum treatment diets included 18 replicates per treatment over the grow-out of 1 to 40 days of age.

Excreta collection and measurements. Excreta collection and other measurements for AME_n determination of grain sorghum was determined in Japanese quail at 3-weeks of age (19 to 21 days) and 6-weeks of age (36 to 38 days). At the end of each collection period, feed disappearance and total excreta weight were measured. A 30-g sample of feed and excreta was analyzed for dry matter, G.E., and nitrogen content with a bomb calorimeter and combustion N analyzer at the University of Georgia Feed, Environmental and Water (FEW) Laboratory (Athens, Georgia). Feed intake (F.I.), excreta weight, G.E., and nitrogen (N) content results were used to calculate the nitrogen corrected AME_n of grain sorghum using the difference method by MacLeod et al. (Macleod et al., 2008):

(1) ***Treatment AME_n:*** $AME_n = [GEI - GEE] - [8.73 \times (NI - NE)] \div FI$

(2) ***Sorghum AME_n:*** $AME_{n\ grain\ sorghum} = AME_{n\ basal} + (AME_{n\ treatment} - AME_{n\ basal}) \div$ (proportion of added grain sorghum)

where GEI = gross energy intake; GEE = gross energy output in excreta; NI = nitrogen intake from the diet; NE = nitrogen output from excreta; FI = feed intake; and 8.73 = nitrogen correction factor from previous research (Titus et al., 1959).

Statistical Analyses. The initial analyses were based on a 2 x 4 factorial treatment design with age (3-weeks and 6-weeks) and grain types (corn/dextrose, red/bronze, white/tan, and U.S. No.2 yellow) defining the treatments, and a randomized complete block experiment design with cage and trials defining the block. The model effects were assessed with ANOVA based on the treatment and experiment designs. No significant evidence was observed for an age and grain type interaction for many of the response variables; therefore, analyses of grain type effects were performed separately for the two ages (3-weeks and 6-weeks). Fisher's Least Significant Difference procedure was used to determine specific differences among the grain type means. P-values ≤ 0.05 were considered evidence of statistical significance. All statistical calculations were performed using JMP Pro version 15.2.0 (SAS Institute Inc., Cary, NC).

Objective 4: Determine the growth rates and economic impact of commercial broilers fed selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum in relation to that of a standard corn-based diet

Materials and methods

All procedures were approved by the Clemson University Institutional Animal Care and Use Committee (AUP #2020-021).

Birds and Husbandry. A total of 640, 1 d-old Cobb 500 x Hubbard male broiler chicks were obtained, and group weighed (20 birds per pen and 8 pens per treatment). Birds were randomly distributed in floor pens, 140 cm x 183 cm, with a bedding of wood shavings in a curtain-sided broiler house. Floor pen dividers were placed in each pen to adhere to commerical stocking density requirements and maintain uniformity across all birds. All birds has access to hanging feeders and an automatic drinking system. A brooder lamp was provided per pen from 1 to 21 days of age, and the temperature of the house was 35ºC at placement and gradually decreased to reach 24ºC with a daily lighting program of 18 hours of light to 6 hours of dark throughout the study.

Treatments. Three tannin-free varieties of grain sorghum, red/bronze, U.S. No. 2 yellow, and white/tan, were sourced from South Carolina, Florida and Texas, respectively. Red/bronze and white/tan grain sorghum varieties were identity preserved, while U.S. No. 2 yellow was a red/bronze based variety that may have contained other mixed grain sorghum varieties. Modern varieties of grain sorghum used in experimental treatments were previously tested to ensure zero tannin content and analysis indicated that no tannins were detected. Each whole grain sorghum was ground through a hammermill with a 4-mm sieve. Treatments were formulated based on an industry standard and prepared as basal starter, grower and finisher diets with each respective test ingredient of corn or grain sorghum. Birds were fed 1 of 4 treatments ad-libitum of crumble/pellet feed according to a three-phase feeding program: starter (1-14 d-of age), grower (15 to 28 d-of-age), and finisher (29 to 42 d-of age).

Growth Performance and Carcass Measurements. Group body weight and feed intake were recorded weekly on days 1, 8, 15, 22, 29, 36, and 42 to determine body weight gain (BWG), feed conversion ratio (FCR), and feed intake (FI). Daily mortality was weighed and recorded for adjusted feed conversion ratio (AdjFCR) calculations. At 41 d-of-age, 1 bird per pen was selected to collect jejunal intestinal tissue samples for histomorphology measurements. On day 42, 2 birds from each pen/treatment were randomly selected based on the average body weight of the pen for slaughter and further processed to obtain carcass yield (CY) and breast yield (BY). Birds were euthanized via electrical stunning, bled, scalded and defeathered. Eviscerated whole carcasses (feet, shanks and neck removed) were individually weighed to measure hot carcass weight. The front half of each carcass with pectoral major and minor muscles (bone-in, skin-on) were removed and individually weighed to measure breast yield. Carcass and breast yields were calculated as a percentage of the initial live weight and hot carcass weight, respectively.

Benefit-Cost Analysis. In this study a cost-benefit analysis was conducted for corn and different grain sorghum varieties in broilers diet. The gross benefit was estimated from U.S. market price reports received per live weight (lb) of birds. The total cost of broilers' diet is the summation of cost of diet ingredients in the starter, grower, and finisher phases. The only variable/control ingredient in each diet is the sorghum variety (e.g., red/bronze sorghum, white/tan sorghum, and U.S. No.2 sorghum) and corn. Price of each ingredient was obtained from the Smithfield Grain database for Darlington, South Carolina (Smithfield Grain, 2021). The mean price received by broilers producer was estimated to be \$0.75/lb as the market price representative in Q2 2021 (Smithfield Grain, 2021). Subsequently, benefit-cost ratio per variable/control ingredient (BCR_i) is calculated as below where *i* indicates the variable ingredient of the diet:

$$BCR_i = \frac{Price\ per\ live\ bird\ weight\ (\$/lb)}{Total\ cost\ of\ diet\ (i)\ per\ live\ bird\ weight\ (\$/lb)}$$

Statistical Analyses. Data were analyzed as a completely randomized design with pen designated as the experimental unit of 20 broilers per pen (n = 640 total birds) phase-fed 1 of the 4 aforementioned diets. Statistical analyses were conducted on performance data of mean pen-grouped birds, including mean body weight (B.W.), average daily gain (ADG), feed intake (F.I.), feed conversion ratio (FCR) and select carcass trait measurements (live weight, carcass weight, bone-in breast meat, abdominal fat, and drip-loss) per bird per treatment using JMP Pro version 14.1.0 (SAS Institute Inc., Cary, NC). A linear fixed effects model evaluated each dependent variable of phase-fed feed intakes and carcass yields from 1 to 42 days of age. Fixed effects of treatment, trial and possible interaction of treatment and trial were assessed using factorial ANOVA. Significant differences between treatment means were determined using Fisher's least significant difference procedure. Mean B.W., mean ADG, mean F.I. and mean FCR over time were evaluated as dependent variables using a linear mixed effects model with treatment, trial, day, treatment*trial, and treatment*day as fixed effects and a random effect of treatment and trial nested within pen. Statistical significance was established at $P \leq 0.05$.

Objective 6: Determine the growth rates and economic impact of Japanese quail fed selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum in relation to that of a standard corn based diet

Materials and Methods

All procedures were approved by the Clemson University Institutional Animal Care and Use Committee (AUP #2017-051).

Birds and Husbandry. One trial evaluated the growth performance and carcass traits of 644 mixed-sex Japanese quail (*Coturnix japonica*) 1 to 40 days of age. Quail were housed in a curtain-sided broiler house, group weighed (n = 14 birds) per cage on day 1 of age, randomly distributed in 46 rabbit wire hutches, 76 cm x 91 cm, (Pet Lodge, Miller Manufacturing, Minnesota), and placed inside floor pens, 183 cm x 305 cm, containing wood shavings as bedding material. Each cage was provided with a trough feeder and quart jar waterer. The temperature of the house was 37ºC at placement and gradually decreased to reach 23ºC with a daily lighting program of 16 hours of light to 8 hours of dark (16L:8D) throughout the study.

Tannin analysis. See Objective 1. Tannin analysis

Treatments. Three modern varieties of grain sorghum commonly grown in the southeastern U.S., red/bronze, white/tan, and U.S. No. 2 Yellow, were obtained from Florida and North Carolina and used for all diets in *Experiments 1* and *2*. The red/bronze and white/tan grain sorghum varieties were identity preserved, while U.S. No. 2 yellow was a red/bronze based variety that may have contained other mixed grain sorghum varieties. Nutrient and gross energy (G.E.) analyses of grain sorghum used in the experimental diets are shown in Table A8. All whole grain sorghum was ground through a hammer mill (Premier 1 Supplies, Washington, Iowa) with a 4-mm sieve.

AME_n values determined for grain sorghum varieties in *Objective 3* were used in diet formulation for the growth performance trial. Japanese quail were fed one phase constituting a starter/grower diet mash ad-libitum from 1 to 40 days of age. Table A15. shows the ingredient compositions and nutrient analyses for Japanese quail diets. All birds were fed a corn-based acclimation diet on days 1 to 3. On day 4, birds were randomly assigned to 1 of 5 treatments including a full inclusion corn diet serving as the control (6 replicates) and full inclusion of red/bronze, white/tan, U.S. No. 2 yellow or a mixture of all three varieties of grain sorghum at equivalent levels (1/3 red/bronze, 1/3 white/tan, and 1/3 U.S. No. 2 yellow) (10 replicates per treatment).

Performance and carcass measurements. Birds were group weighed (kg/cage), and feed disappearance was measured weekly on days 1, 8, 15, 22, 29, 36, and 40. Weekly measures of mean body weight (B.W.) and feed disappearance were used to calculate mean F.I. and feed conversion ratio (FCR) per treatment:

(3) $\mathbf{FCR_{1\text{-}40\ days\ of\ age}}$**, (not adjusted for mortality)** = mean $FI_{1\text{-}40\ days\ of\ age}$ ÷ mean $BWG_{1\text{-}40\ days\ of\ age}$

At 40 days of age, feed was withdrawn, and birds fasted for 12-hours before slaughter, an accepted industry standard procedure. All birds were group weighed per pen and treatment, and 6 birds from each replicate were randomly selected, group weighed for total live body weight (LBW), and transported to the meat laboratory at Clemson University for slaughter and further processing. Birds were euthanized via cervical dislocation, and eviscerated whole carcasses were individually weighed to measure hot carcass weight (HCW) and carcass yield (C.Y.). All carcasses were placed on ice and stored at 3ºC for 24 hours. Then, whole carcasses were drained to remove excess water and weighed to obtain chilled carcass weight. Next, the front half of each carcass with pectoral major and minor muscles (bone-in) were removed and individually weighed to measure breast weight (BrW) and breast yield (BrY). Carcass and breast yields were calculated as a percentage of HCW.

Statistical Analyses. Data were analyzed as a completely randomized design with pen designated as the experimental unit of 14 Japanese quail per pen (n = 644 birds) fed 1 of the 5 aforementioned diets. Statistical analyses were conducted on performance data of mean pen-grouped birds, including mean B.W., F.I., FCR, and select individual bird carcass trait measurements (HCW, CY, BrW, and BrY) per treatment. The analyses were based on a linear model with a fixed effect of treatment. The treatment effect was assessed with ANOVA, and Fisher's Least Significant Difference procedure was performed to determine specific differences between treatment means. The fixed effects of sex (% male and % female per pen) for sample birds at slaughter and sex by diet interaction were considered, but not included in the final model, since the effects were found to not be significant based on ANOVA. In addition, according to the experimental design protocol, mean body weight per individual bird was calculated. The effect of individual bird weight was also considered in the model as a covariate; however, using the Analysis with individual body weight values resulted in comparisons of treatments consistent with the Analysis for mean pen weights. Therefore, mean body weight per bird per pen was used as the response variable in the statistical models. P-values $\leq$ 0.05 were considered evidence of statistical significance. All statistical calculations were performed using JMP Pro version 15.2.0 (SAS Institute Inc., Cary, NC).

Benefit-Cost Analysis. The gross benefit was estimated from U.S. market price reports received per live weight (lb) of birds. It was assumed that there is no body weight change between treatment. The study was conducted based on five different diets where the only control/variable ingredient of each diet was corn, red/bronze sorghum, white/tan sorghum, U.S. No.2 sorghum, and mixed sorghum. The price of ingredients in each diet was obtained from Smithfield Grain database for Darlington, South Carolina (Smithfield Grain, 2021). The mean sale price received by Japanese quail producer was estimated to be \$5.56/lb as the market price representative in Q2 2021 (Manchester Farms, 2021). Subsequently, benefit-cost ratio (BCR) per control/variable ingredient (i) is calculated as below where *i* indicates the variable ingredient of the diet:

$$BCR_i = \frac{Price\ per\ live\ bird\ weight\ (\$/lb)}{Total\ cost\ of\ diet\ (i)\ per\ live\ bird\ weight\ (\$/lb)}$$

Results

Objective 1. <u>Determine the apparent metabolizable energy (AME) value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding commercial broilers to target weight</u>

AME_n determination. Determined AME_n for grain sorghum in the grower phase (22 to 24 day-of-age) presented in Table 1. were 3,326 (red/bronze), 3,288 (white/tan), and 2,546 (U.S. No. 2 Yellow) kcal/kg. Red/bronze had the highest AME_n compared to corn, and white/tan was intermediate (P = 0.0094). In the finisher phase (43 to 45 day-of-age), shown in Table 4., the determined AME_n was 3,409 (red/bronze), 3,535 (white/tan), and 3,736 (U.S. No. 2 Yellow) kcal/kg. U.S. No. 2 yellow had the highest AME_n compared to corn, and both red/bronze and white/tan were intermediate (P = 0.0253). Relative to AME_n determination, feed intake was highest in the finisher phase (P = 0.0075).

Growth performance. Growth performance responses including B.W., F.I., and FCR are shown in Table 2. for the grower and finisher diet-phases corresponding to each period for AME_n determination on 22 and 43 days of age. Responses were not negatively affected by grain sorghum treatments compared to corn as shown with no significant differences in body weight for both diet phases and F.I. and FCR for the finisher diet phase. U.S. No. 2 yellow and red/bronze had the highest feed intakes in the grower and finisher-diet phases compared to white/tan and corn. FCR showed white/tan and corn with significantly better conversion than red/bronze and U.S. No.2 yellow (P = 0.0034).

Table 1. Mean apparent metabolizable energy (AME_n), and 72-hr. feed intake by treatment (corn/dextrose, red/bronze, white/tan, and U.S. No. 2 Yellow grain sorghum) during the grower and finisher-diet phases of the excreta collection period, 22 to 24 d of age and 43 to 45 d of age, in commercial broilers.

	Treatment	**Diet Phase**	
$AME_{n\ grain,}$ (kcal/kg)		Grower	Finisher
	Corn/Dextrose	3,100 ± 529.66[ab]	3,099 ± 195.09[b]
	Red/Bronze	3,315 ± 529.66[a]	3,410 ± 160.63[ab]
	White/Tan	3,306 ± 517.70[a]	3,534 ± 161.82[a]
	U.S. No. 2 Yellow	2,659 ± 520.73[b]	3,702 ± 166.48[a]
	P-value	0.0064*	0.0436*
72-hr Feed Intake, (kg)			
	Corn/Dextrose	1.54 ± 0.15	2.21 ± 0.24[ab]
	Red/Bronze	1.67 ± 0.14	2.13 ± 0.22[b]
	White/Tan	1.74 ± 0.14	2.47 ± 0.22[a]
	U.S. No. 2 Yellow	1.66 ± 0.14	2.45 ± 0.23[a]
	P-value	0.3400	0.0168*

*Statistical significance: $P \leq 0.05$

[1]LSMeans ± SEM; each means represents 8 cages with 4 birds/cage for control, and 16 cages with 4 birds/cage per treatment of red-bronze, white-tan, and U.S. No. 2 Yellow.

[a-b] Means within the same column connected by the same letter are not significantly different.

Table 2. Effect of corn, red/bronze, white/tan, and U.S. No. 2 Yellow grain sorghum on growth performance responses (B.W., F.I., and FCR) of broilers during the grower and finisher-diet phases at 15-22 days of age and 36-43 days of age, respectively.

Treatment[1]	Diet Phase		
	Grower		
	BW[2] (kg/bird)	FI[2] (kg/bird)	FCR[2] (kg/kg)
Corn/dextrose	0.92 ± 0.02	0.64 ± 0.06[b]	1.33 ± 0.14[b]
Red/Bronze	0.94 ± 0.01	0.75 ± 0.04[ab]	1.70 ± 0.12[a]
White/Tan	0.93 ± 0.01	0.69 ± 0.04[b]	1.42 ± 0.12[b]
U.S. No. 2 Yellow	0.93 ± 0.01	0.80 ± 0.04[a]	1.67 ± 0.12[a]
***P*-value**	0.9000	0.0225*	0.0034*
	Finisher		
	BW[2] (kg/bird)	FI[2] (kg/bird)	FCR[2] (kg/kg)
Corn/dextrose	2.98 ± 0.11	1.20 ± 0.11	1.52 ± 0.25
Red/Bronze	3.03 ± 0.07	1.40 ± 0.08	1.92 ± 0.17
White/Tan	3.10 ± 0.07	1.27 ± 0.08	1.84 ± 0.17
U.S. No. 2 Yellow	2.93 ± 0.07	1.50 ± 0.08	2.35 ± 0.17
***P*-value**	0.5276	0.0945	0.0715

[1]LSMeans ± SEM; each means represents 8 cages with 4 birds/cage (kg/bird) for control, and 16 cages with 4 birds/cage (kg/bird) per treatment for red/bronze, white/tan, and U.S. No. 2 Yellow.
[2] Measurement abbreviations: BW = body weight; FI = feed intake; FCR = feed conversion ratio
*Statistical significance: $P \leq 0.05$.
[a-b] Means within the same column connected by the same letter are not significantly different.

Objective 2. Determine the AME value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding bobwhite quail to target weight/age

The determined AME_n for grain sorghum at 6-weeks of age presented in Table 3. were 3,610 (red/bronze), 3,544 (white/tan), and 3,577 (U.S. No. 2 Yellow) kcal/kg. At 11-weeks of age, the determined AME_n, shown in Table 4, were 3,311 (red/bronze), 3,297 (white/tan), and 2,497 (U.S. No. 2 Yellow) kcal/kg. No significant differences were observed in the AME value and 96-hr F.I. at 6 and 11-weeks of age (*P* >

0.05). No significant differences were observed in BW, FI or FCR at 6 and 11 weeks of age ($P > 0.05$).

Table 3. Mean apparent metabolizable energy (AME_n), and 96-hr. feed intake by treatment (corn/dextrose, red/bronze, white/tan, and U.S. No. 2 Yellow grain sorghum) during the excreta collection period, at 6-weeks (41 to 44 d of age) and 11-weeks (79 to 82 d of age), in Bobwhite quail.

	Age	
$AME_{n\ grain,}$ (kcal/kg)	**6-weeks**	**11-weeks**
Corn/Dextrose	3,601 ± 269.79	3,508 ± 451.58
Red/Bronze	3,610 ± 268.18	3,311 ± 451.56
White/Tan	3,544 ± 268.61	3,297 ± 452.82
U.S. No. 2 Yellow	3,577 ± 272.56	3,497 ± 455.54
***P*-value**	0.9786	0.5173
96-hr Feed Intake, (kg)		
Corn/Dextrose	0.481 ± 0.01	0.252 ± 0.02
Red/Bronze	0.446 ± 0.01	0.240 ± 0.02
White/Tan	0.460 ± 0.02	0.231 ± 0.02
U.S. No. 2 Yellow	0.490 ± 0.02	0.243 ± 0.02
***P*-value**	0.6549	0.5586

*Statistical significance: $P \leq 0.05$
[1]LSMeans ± SE; each means represents 10 cages with 5 birds/cage for control, red bronze, white-tan, and U.S. No. 2 Yellow treatments.
[a-c] Means within the same column connected by the same letter are not significantly different.

Table 4. Effect of corn, red/bronze, white/tan, and U.S. No. 2 Yellow grain sorghum on growth performance responses (BW, FI and FCR) of Bobwhite quail at 6-weeks and 11-weeks of age.

Treatment[1]	Age		
	6-weeks		
	BW[2] (kg/bird)	FI[2] (kg/bird)	FCR[2] (kg/kg)
Corn/dextrose	0.113 ± 0.007	0.079 ± 0.003	3.35 ± 0.252
Red/Bronze	0.121 ± 0.007	0.084 ± 0.004	3.16 ± 0.252
White/Tan	0.116 ± 0.007	0.084 ± 0.005	3.49 ± 0.257
U.S. No. 2 Yellow	0.111 ± 0.007	0.079 ± 0.005	3.74 ± 0.268
***P*-value**	0.6581	0.6630	0.2411
	11-weeks		
	BW[2] (kg/bird)	FI[2] (kg/bird)	FCR[2] (kg/kg)
Corn/dextrose	0.175 ± 0.006	0.129 ± 0.026	3.45 ± 0.587
Red/Bronze	0.173 ± 0.006	0.132 ± 0.026	3.38 ± 0.589
White/Tan	0.176 ± 0.006	0.153 ± 0.026	3.59 ± 0.593
U.S. No. 2 Yellow	0.171 ± 0.006	0.127 ± 0.027	3.47 ± 0.598
***P*-value**	0.9041	0.2664	0.8995

[1]LSMeans ± SEM; each means represents 10 cages with 5 birds/cage (kg/bird) for control, red/bronze, white/tan, and U.S. No. 2 Yellow.
[2] Measurement abbreviations: BW = body weight; FI = feed intake; FCR = feed conversion ratio
*Statistical significance: $P \leq 0.05$.
[a-b] Means within the same column connected by the same letter are not significantly different.

Objective 3. Determine the AME value of selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum for feeding Japanese quail to target weight/age

The determined AME_n for grain sorghum at 3-weeks of age presented in Table 5. were 3,524 (red/bronze), 3,252 (white/tan), and 3,039 (U.S. No. 2 Yellow) kcal/kg. Red/bronze had the highest AME_n compared to corn/dextrose, white/tan, and U.S. No. 2 Yellow (P = <0.0001). At 6-weeks of age, the determined AME_n, shown in Table 5, were 3,373 (red/bronze), 3,279 (white/tan), and 2,966 (U.S. No. 2 Yellow) kcal/kg. The highest determined AME_n was the red/bronze grain sorghum, while white tan was intermediate when compared to U.S. No. 2 yellow (P = 0.0322). No significant differences were observed in the 72-hr F.I. at 3 and 6-weeks of age ($P > 0.05$). Average mortality for this experiment was 4% for corn-dextrose, 3% for red/bronze, 8% for white/tan, and 9% for U.S. No. 2 yellow treatments ($P > 0.05$).

Table 5. Mean apparent metabolizable energy (AME_n), and 72-hr. feed intake by treatment (corn/dextrose, red/bronze, white/tan, and U.S. No. 2 Yellow grain sorghum) during the excreta collection period, at 3-weeks (19 to 21 d of age) and 6-weeks (36 to 38 d of age), in Japanese quail.

	Age	
$AME_{n\ grain,}$ (kcal/kg)	**3-weeks**	**6-weeks**
Corn/Dextrose	3,106 ± 134.30[bc]	3,106 ± 309.18[ab]
Red/Bronze	3,524 ± 122.03[a]	3,373 ± 297.35[a]
White/Tan	3,252 ± 122.03[b]	3,279 ± 297.35[a]
U.S. No. 2 Yellow	3,039 ± 123.44[c]	2,966 ± 298.64[b]
P-value	<0.0001*	0.0322*
72-hr Feed Intake, (kg)		
Corn/Dextrose	0.496 ± 0.07	0.362 ± 0.03
Red/Bronze	0.496 ± 0.07	0.359 ± 0.02
White/Tan	0.495 ± 0.07	0.341 ± 0.02
U.S. No. 2 Yellow	0.502 ± 0.07	0.334 ± 0.02
P-value	0.9981	0.6211

*Statistical significance: P < 0.05
[1]LSMeans ± S.E.; each means represents 10 cages with 5 birds/cage for control, and 18 cages with 5 birds/cage for red bronze, white-tan, and U.S. No. 2 Yellow.
[a-c] Means within the same column connected by the same letter are not significantly different.

Objective 4. Determine the growth rates and economic impact of commercial broilers fed selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum in relation to that of a standard corn-based diet

Growth performance and carcass traits. Growth performance in Table 6. shows the greatest B.W. observed in the corn-based diet treatment compared to red/bronze, white/tan, and U.S. No. 2 yellow treatments (*P* = 0.0048). Birds fed corn and red/bronze-based diets had higher feed intakes than those fed the U.S. No.2 yellow, while white/tan treatment was intermediate (P = 0.0261). No significant differences were observed among treatments for Adj. FCR or mortality. The high mortalities could be explained due to accelerated growth during the grower phase caused by higher than expected feed intakes. Also, due to unexpected lower calcium levels in the diets. Carcass traits in Table 7 show LBW (*P* = 0.0147) and HCW (*P* = 0.0288) were greatest in the corn-based (standard) compared to red/bronze and white/tan diets, while U.S. No. 2 yellow was intermediate. No significant differences were observed among treatments for CY, BrW, and BY (*P* > 0.05).

Table 6. Effect of treatment (standard, red/bronze, white/tan, U.S. No. 2 Yellow) on growth performance responses, BWG, F.I., and Adj. FCR, for broiler chickens 1 to 42 days of age.

Treatment[1]	BWG[2] (kg/bird)	FI[2] (kg/bird)	Adj. FCR[2]	% Mortality
Standard	3.62[a] ± 0.064	7.31[a] ±0.236	2.15 ± 0.092	17.26 ± 2.66
Red/Bronze	3.48[b] ± 0.064	7.27[a] ± 0.236	2.06 ± 0.092	10.08 ± 2.66
White/Tan	3.52[b] ± 0.064	7.10[ab] ± 0.236	1.97 ± 0.092	11.30 ± 2.66
U.S. No. 2 Yellow	3.48[b] ± 0.064	6.86[b] ± 0.236	1.92 ± 0.092	13.10 ± 2.66
***P*-value**	0.0048*	0.0261*	0.3317	0.2656

[1]LSMeans ± SEM; each means represents 8 pens with 20 birds/pen (kg/bird) per treatment for standard, red/bronze, white/tan, and U.S. No. 2 Yellow.
[2] Measurement abbreviations: BWG = body weight gain; FI = feed intake; Adj. FCR = adjusted feed conversion ratio
[a-b]Means within the same column connected by the same letter are not significantly different.
*Statistical significance: $P \leq 0.05$.

Table 7. Effect of treatment (standard, red/bronze, white/tan, U.S. No. 2 Yellow) on carcass traits for broiler chickens 1 to 42 days of age.

Measurement[1]	Treatments Standard	Red/Bronze	White/Tan	U.S. No. 2 Yellow	*P*-value
LBW[3] (kg/bird)	3.54 ± 0.06[a]	3.40 ± 0.06[b]	3.40 ± 0.06[b]	3.45 ± 0.06[ab]	0.0147*
HCW[3] (kg/bird)	2.76 ± 0.08[a]	2.63 ± 0.08[b]	2.35 ± 0.08[b]	2.67 ± 0.08[ab]	0.0288*
CY[3] (%)	78.05 ± 0.77	76.88 ± 0.77	77.04 ± 0.77	77.19 ± 0.77	0.6698
BrW[3] (kg/bird)	1.08 ± 0.05	1.03 ± 0.05	1.02 ± 0.05	1.05 ± 0.05	0.4777
BrY[3] (%)	39.38 ± 0.62	39.24 ± 0.62	38.46 ± 0.62	39.39 ± 0.62	0.7136

[1]Measurement abbreviations: LBW = live body weight; HCW = hot carcass weight; CY = carcass yield; BrW = breast weight (bone-in); BrY = breast yield; LSMeans ± SE; each means represents 8 replicate pens for 2 birds (kg/bird) per treatment.
[a-b] Means within a row connected by the same letter are not significantly different.
*Statistical significance: $P \leq 0.05$.

Benefit-Cost Analysis per diet. It was assumed that the only difference in each diet is the control ingredient (corn, U.S. No. 2 yellow, red/bronze, and white/tan). Hereafter these diets are called corn-based, red/bronze-based, white/tan-based, and U.S. No. 2 yellow-based diet. Based on the estimated live weight price and obtained cost information from producers, calculated BCR per diet for broilers is shown in Table 8. Given that cost of 1lb of corn is \$0.12 and 1lb of any verity of sorghum costs \$0.14, the benefit-cost ratio (BCR) calculation shows that corn-based diet has the highest BCR and the second highest BCR for broilers belongs to the red/bronze-based diet. To separate the effect of the quantity of variable ingredients from their price in the BCR analysis, in second row of table 8, it was assumed that the price of corn and sorghums are the same. Thus, the only variable factor in the BCR analysis, is the amount of corn, red/bronze, white/tan, and U.S. No. 2 yellow sorghum that each bird consumes. Considering this assumption, still corn-based diet is the most cost-effective diet for broilers producers.

Table 8- Benefit-Cost Ratio (BCR) of different diets for broilers

Diet **BCR**	**Corn-based**	**Red/bronze-based**	**White/tan-based**	**U.S. No. 2 yellow-based**
When 1lb of corn costs $0.12 and 1lb of any verity of sorghum costs $0.14	3.63	3.31	3.08	3.06
When 1lb of corn and 1lb of any verity of sorghum costs $0.12	3.63	3.59	3.31	3.29

Objective 6. Determine the growth rates and economic impact of Japanese quail fed selected modern varieties (tan and/or white, red and/or bronze, and U.S. No. 2 yellow) of grain sorghum in relation to that of a standard corn based diet

Growth performance and carcass traits. Growth performance in Table 9. shows the greatest B.W. observed in the U.S. No. 2 yellow treatment compared to corn, red/bronze, and white/tan treatments ($P = 0.0031$); the mixture of all three grain sorghum varieties showed an intermediate B.W. relative to the other treatments. No significant differences were observed among treatment for F.I. and FCR ($P > 0.05$). Birds in the U.S. No. 2 yellow treatment had the highest mortality of 25.71%, while corn was observed to have the lowest at 11.90% and red/bronze, white/tan, and mixed treatments were intermediate (22.14%, 22.14%, and 18.57%, respectively) ($P = 0.0181$). Carcass traits in Table 10. show LBW ($P = 0.0409$) and HCW ($P = 0.0234$) were greatest in U.S. No. 2 yellow compared to all other treatments; however, C.Y. ($P = < 0.0001$) was lowest in the U.S. No. 2 yellow treatment. No significant differences were observed among treatments for BrW and BY ($P > 0.05$).

Table 9. Effect of treatment (control, red/bronze, white/tan, U.S. No. 2 Yellow and mixed (1/3 of each of the 3 varieties of grain sorghum) on growth performance responses (B.W., F.I., and FCR) for Japanese quail 1–40 days of age.

Treatment[1]	**BW**[2] **(kg/bird)**	**FI**[2] **(kg/bird)**	**FCR**[2] **(kg/kg)**	**% Mortality**
Corn	$0.210^{b} \pm 0.006$	0.543 ± 0.034	2.75 ± 0.178	$11.90^{c} \pm 3.15$
Red/Bronze	$0.206^{b} \pm 0.005$	0.545 ± 0.054	2.76 ± 0.138	$22.14^{ab} \pm 2.44$
White/Tan	$0.204^{b} \pm 0.005$	0.576 ± 0.054	2.93 ± 0.138	$22.14^{ab} \pm 2.44$
U.S. No. 2 Yellow	$0.228^{a} \pm 0.005$	0.575 ± 0.054	2.81 ± 0.138	$25.71^{a} \pm 2.44$
Mixed	$0.216^{ab} \pm 0.005$	0.540 ± 0.054	2.71 ± 0.138	$18.57^{bc} \pm 2.51$
***P*-value**	0.0031*	0.7824	0.8336	0.0181*

[1]LSMeans ± SEM; each means represents 6 pens with 14 birds/pen (kg/bird) for control, and 10 pens with 14 birds/cage (kg/bird) per treatment for red/bronze, white/tan, U.S. No. 2 Yellow, and mixed.
[2] Measurement abbreviations: BW = body weight; FI = feed intake; FCR = feed conversion ratio
[a-c] Means within the same column connected by the same letter are not significantly different.
*Statistical significance: P ≤ 0.05.

Table 10. Effect of treatment (control, red/bronze, white/tan, U.S. No. 2 Yellow and mixed (1/3 of each of the 3 varieties of grain sorghum) on carcass traits in Japanese quail in *Experiment 2*.

Measurement[2]	Treatments[1]					*P*-value
	C	RB	WT	Y	M	
LBW[3] (kg/bird)	0.203 $\pm$ 0.005[b]	0.208 $\pm$ 0.003[b]	0.207 $\pm$ 0.003[b]	0.220 $\pm$ 0.003[a]	0.205 $\pm$ 0.003[b]	0.0409*
HCW[3] (kg/bird)	0.034 $\pm$ 0.0008[b]	0.035 $\pm$ 0.0006[b]	0.034 $\pm$ 0.0006[b]	0.037 $\pm$ 0.0006[a]	0.034 $\pm$ 0.0006[b]	0.0234*
CY[3] (%)	77.89 $\pm$ 1.32[a]	77.61 $\pm$ 0.877 [a]	75.36 $\pm$ 0.877 [a]	70.33 $\pm$ 0.877 [b]	77.71 $\pm$ 0.877 [a]	< 0.0001*
BrW[3] (kg/bird)	0.052 $\pm$ 0.004	0.052 $\pm$ 0.003	0.057 $\pm$ 0.003	0.051 $\pm$ 0.004	0.050 $\pm$ 0.003	0.4751
BrY[3] (%)	32.78 $\pm$ 2.34	32.33 $\pm$ 1.82	36.70 $\pm$ 1.82	33.16 $\pm$ 1.82	31.13 $\pm$ 1.82	0.2800

[1]Treatment abbreviations: C = corn; RB = red/bronze; WT = white/tan; Y = U.S. No. 2 Yellow; M = mixed
[2]LSMeans $\pm$ SE; each means represents 6 replicate pens for 6 birds (kg/bird) per C treatment, and 10 replicate pens of 6 birds (kg/bird) per RB, WT, Y, and M grain sorghum treatment.
[3] Measurement abbreviations: LBW = live body weight; HCW = hot carcass weight; CY = carcass yield; BrW = breast weight (bone-in); BrY = breast yield
[a-b] Means within a row connected by the same letter are not significantly different.
*Statistical significance: $P < 0.05$.

Benefit-Cost Analysis per ingredient. It was assumed that the only difference in each diet is the control ingredient (corn, U.S. No. 2 yellow, red/bronze, and white/tan). Hereafter these diets are called corn-based, red/bronze-based, white/tan-based, and U.S. No. 2 yellow-based diet. Based on the estimated live weight price and obtained cost information from producers, calculated BCR per diet for Japanese quails is shown in Table 1. Given that cost of 1lb of corn is \$0.12 and 1lb of any verity of sorghum costs \$0.14, benefit-cost ratio (BCR) calculation shows that corn-based diet has the highest BCR and the second highest BCR for broilers belongs to the red/bronze-based diet. To separate the effect of the quantity of variable ingredients from their price in the BCR analysis, in second row of table 11, it was assumed that the price of corn and sorghums are the same. Thus, the only variable factor in the BCR analysis, is the amount of corn, red/bronze, white/tan, and U.S. No. 2 yellow sorghum that each bird consumes. Considering this assumption, red/bronze-based diet becomes the most cost-effective diet for Japanese quail producers.

Table 11- Benefit-Cost Ratio of different diets for Japanese quails

Diet / BCR	**Corn-based**	**Red/bronze-based**	**White/tan-based**	**U.S. No. 2 yellow-based**	**Mixed sorghum-based**
When 1lb of corn costs \$0.12 and 1lb of any verity of sorghum costs \$0.14	24.17	23.17	22.69	21.80	22.24
When 1lb of corn and 1lb of any verity of sorghum costs \$0.12	24.17	24.49	23.76	22.69	23.56

Conclusions

Objective 1. The mean AME_n values of modern grain sorghum varieties for broilers in the grower diet-phase were determined as 3,326 (red/bronze), 3,288 (white/tan), and 2,546 (U.S. No. 2 Yellow) kcal/kg, respectively. In the finisher diet-phase, average AME_n values were determined as 3,409 (red/bronze), 3,535 (white/tan), and 3,736 (U.S. No. 2 Yellow) kcal/kg, respectively. In conclusion, AME_n determination for broilers indicates that modern grain sorghum varieties show potential for replacing corn in diet formulation without sacrificing important performance factors, including B.W., F.I., and FCR.

Objective 2. AME_n for grain sorghum at 6-weeks of age were 3,610 (red/bronze), 3,544 (white/tan), and 3,577 (U.S. No. 2 Yellow) kcal/kg. At 11-weeks of age, the determined AME_n values were 3,311 (red/bronze), 3,297 (white/tan), and 2,497 (U.S. No. 2 Yellow) kcal/kg. No significant differences were observed in the AME value and 96-hr F.I. at 6 and 11-weeks of age ($P > 0.05$). No significant differences were observed in BW, FI or FCR at 6 and 11 weeks of age ($P > 0.05$).

Objective 3. Mean AME_n values of modern grain sorghum varieties for Japanese quail at 3-weeks of age were determined as 3,524 (red/bronze), 3,252 (white/tan), and 3,039 (U.S. No. 2 Yellow) kcal/kg, respectively. At 6-weeks of age, average AME_n values were determined as 3,373 (red/bronze), 3,279 (white/tan), and 2,966 (U.S. No. 2 Yellow) kcal/kg., respectively.

Objective 4. Growth performance trials validated determined AME_n values for broiler chickens. They indicated that modern grain sorghum varieties show potential for replacing corn at complete substitution in diet formulation without negatively affecting FCR and carcass traits, including carcass yield, breast weight, and breast yield. In addition, benefit-cost ratio (BCR) analysis revealed that the corn diet has the highest BCR and the second highest BCR for broilers belongs to the red/bronze-based diet.

Objective 6. Growth performance trials validated determined AME_n values for Japanese quail and indicated that modern grain sorghum varieties showed potential for replacing corn at full-substitution in diet formulation without negatively affecting performance factors, including B.W., F.I., FCR as well as carcass traits including hot carcass weight, carcass yield, breast weight, and breast yield. The inclusion level of grain sorghum in diet formulation will be dependent on the cost and availability of grain. BCR analysis showed that the corn-based diet had the highest BCR, followed by Red/bronze sorghum, assuming that cost of 1lb of corn and any variety of sorghum were \$0.12 and \$0.14, respectively. However, when the cost of sorghum was the same as corn, red/bronze-based diet becomes the most cost-effective diet for Japanese quail producers.

Impact

Farmers need water efficient crops to maximize yield during favorable years and minimize losses during dry years. Sorghum is tolerant to dry, sandy soils, which allows it to grow successfully in the Southeastern U.S. Sorghum is highly desirable for production because of its potential to alleviate the production pressure of growing other cereal grains like corn that are less tolerant to variable climate and soil types. Sorghum has shown to yield more bushels per acre on marginal land in SC, which is due to its inherent water- and nutrient-use efficiency. Adding sorghum into farm rotations will help to decrease incidence of important diseases and diversify the use of herbicides.

For 2020, the National Chicken Council reported the use of more than 1.4 billion bushels of corn for broiler, pullet, and breeder feed production. This figure is 3.7 times the number of bushels of grain sorghum produced in the U.S. for the same year. Despite the high demand for cereal grains in poultry diets, sorghum comprises a limited fraction of the industry's total grain. This phenomenon could be attributed to two factors: (1) misconception about the tannin content of modern variates of grain sorghum and (2) transportation costs from sorghum growers (most located west of the Mississippi River) to broiler integrations and the biggest quail grower (mainly located in the Southeastern U.S.). The nutritional and benefit-cost ratio information generated from this research provides the producer/nutritionist with valuable information for designing diets containing sorghum in replacement of corn. As such, this represents a positive step towards the acceptance of grain sorghum as an alternative to corn in the U.S., helping to motivate more poultry integrators to include grain sorghum or increase inclusion rates that were already in use. This will provide poultry producers an additional source of energy for production allowing flexibility from season to season as corn prices fluctuate.

However, more research is needed to provide additional information concerning nutraceuticals content and potential beneficial effects, potential anti-quality factor presence and mitigation, nutrient content as affected by environmental growing conditions as well as storage condition effects and optimal inclusion rates in diets. Amassing this type of data in conjunction with that already attained will build a strong dossier research data need to improve confidence of poultry nutritionists in sorghum grain utilization in order to promote increased utilization of sorghum in poultry and gamebird diets.

Next Steps

- In the grow-out trial (Objective 4), feed intake for broiler chickens was reduced when fed the No. 2 yellow sorghum diet, affecting final body weight. Since this is the commercial product most likely to be acquired by poultry integrators, it will be reasonable to decipher the causes for this response.
- While the results from this project suggest that sorghum can substitute corn in poultry diets, it is unlikely that poultry integrators will quickly adopt a full-substitution approach, as more studies that replicate our results are needed. However, studying the inclusion of grain sorghum on dose-response trials could help validate previous results using full substitution of corn, plus could help find optimal grain combinations to maximize growth performance, health, and livability.
- Recent findings suggest that the abundance of secondary metabolites (nutraceuticals) associated with antimicrobial function may directly impact the control of common poultry intestinal diseases like coccidiosis and necrotic enteritis (N.E.). Therefore, it will be helpful to determine the effectiveness of sorghum hybrids in reducing the incidence and severity of intestinal diseases using a necrotic enteritis challenge model.
- Some secondary metabolites may be beneficial at low rates but not so beneficial at higher rates (anti-quality effect) – thus, understanding the type, content, and beneficial and negative effects of these compounds as well as mitigation strategies when potential issues arise as a result of secondary metabolites is needed to maximize the use of the sorghum in poultry and gamebird diets.
- As particle size and feed presentation are extremely important for broiler performance, evaluating the particle size of sorghum and its effect on pellet quality will be of interest.

Appendix

Tables and Figures

Objective 1.

Figure A1. Tannin analysis of modern varieties of grain sorghum (red/bronze, white/tan, and U.S. No. 2 Yellow) using the acid-butanol assay method. Absorbance peak at 550nm is characteristic of a pure sorghum tannin (pink colored line). Modern grain sorghum varieties did not yield any product at 550nm, indicating that no tannins were detected.

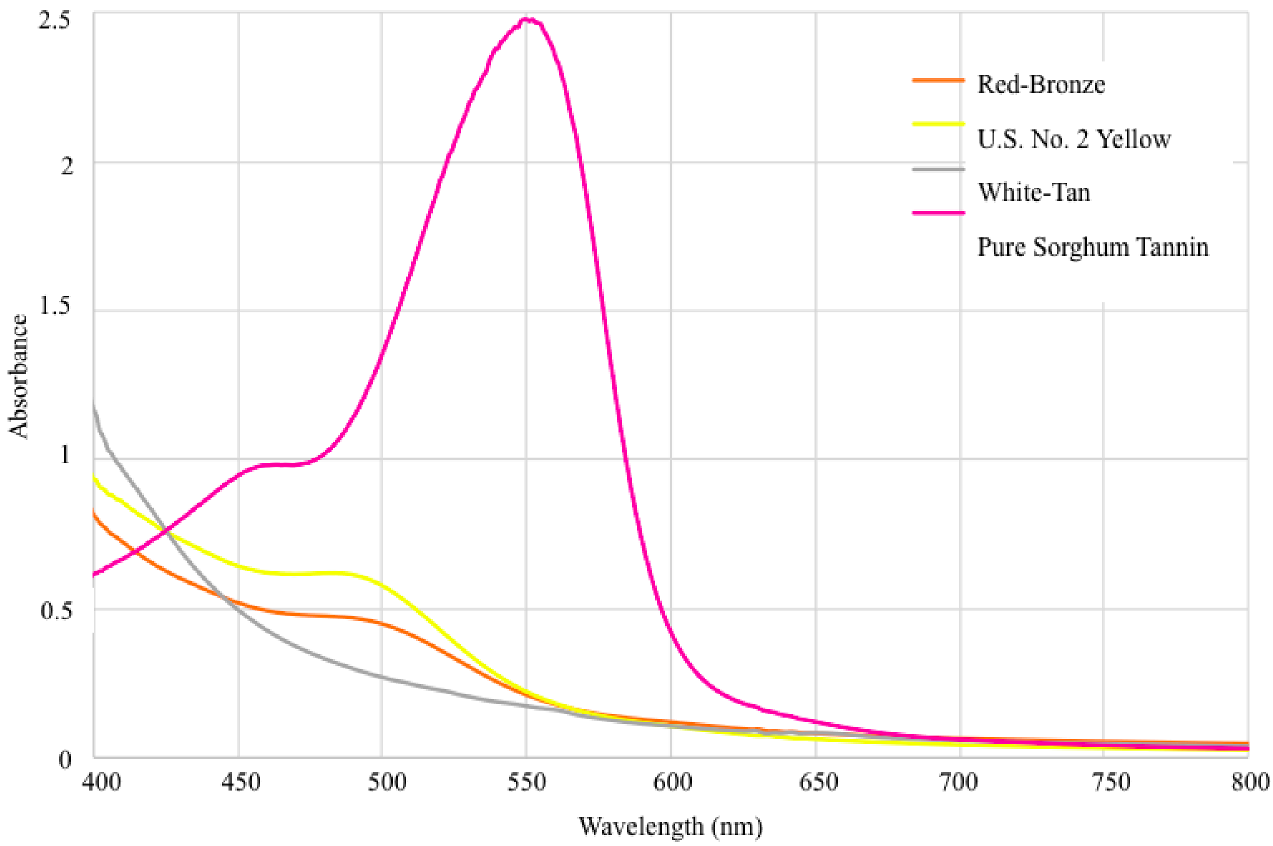

Figure A2. Red/bronze grain sorghum was analyzed at two concentrations to verify that no traces of tannin were detected with larger sample sizes. Spectra for low and high red/bronze grain sorghum indicated no peak at 550nm.

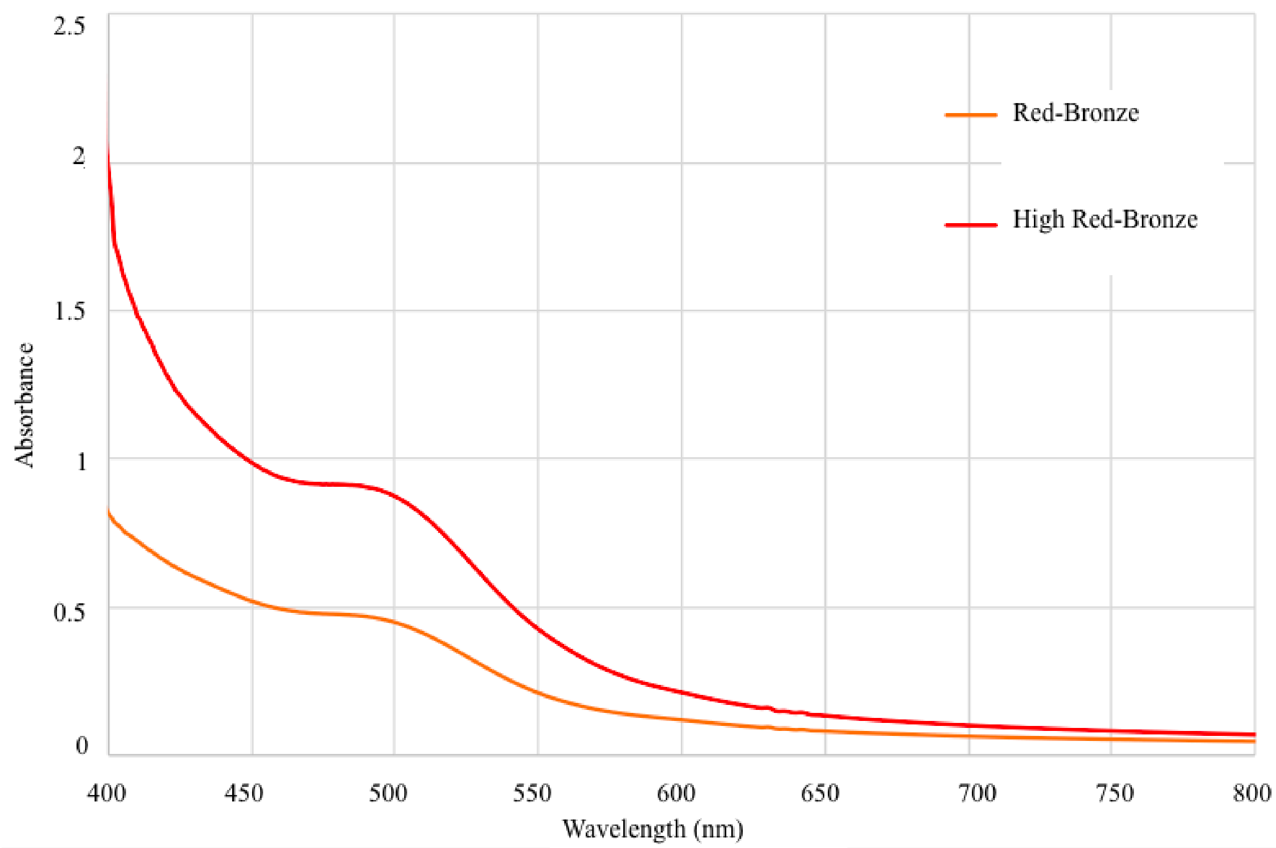

Table A1. Nutrient and gross energy analyses of sources of corn and modern varieties of grain sorghum (red/bronze, white/tan and U.S. No. 2 Yellow).

		Grain Sorghum Variety		
	Corn	Red/Bronze	White/Tan	U.S. No. 2 Yellow
Proximates (%)[1]				
Dry matter	84.58	87.48	89.93	84.44
GE, as-fed (kcal/kg)[2]	3,926	3,752	3,686	3,653
Ash	1.07	0.90	1.10	1.39
Crude fat	3.13	2.89	2.46	2.93
Crude fiber	1.50	1.80	1.70	2.20
Crude protein	7.52	8.87	9.33	8.65
Methionine	0.15	0.15	0.17	0.14
Lysine	0.26	0.24	0.24	0.23
Threonine	0.26	0.30	0.31	0.28

[1]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).
[2]Determined by University of Georgia Feed, Environmental and Water (FEW) Laboratory (Athens, GA).

Table A2. Ingredient composition of basal broiler diet (as-fed) in phases from a 1 to 47 day grow-out for complete test diets (as-fed).

	Basal Diet Phase		
	Starter (1-11 d)	**Grower (12-24 d)**	**Finisher (25-47 d)**
Ingredient (%)			
Corn	49.45	58.60	63.11
Soybean meal, 47.5% CP	42.05	33.55	28.81
Fat, vegetable	3.59	2.96	3.47
Mono-dicalcium phosphate	1.89	1.83	1.73
Limestone	1.57	1.56	1.50
Sodium chloride	0.55	0.59	0.60
DL-methionine	0.33	0.28	0.24
L-threonine	0.00	0.005	0.01
Biolys	0.05	0.10	0.11
Choline chloride, 60%	0.18	0.19	0.12
Vitamin and mineral premix[1]	0.22	0.23	0.20
BMD 50[2]	0.06	0.06	0.06
Saccox 60[3]	0.06	0.05	0.04
Calculated $AME_{n\ basal}$ (D.M., kcal)	---	2,526	2,649
Calculated Composition[4]			
ME (kcal/kg)	2,983	3,039	3,125
Crude protein (%)	23.62	20.38	18.51
Crude fat (%)	6.11	5.68	6.27
Calcium (%)	1.02	0.98	0.94
Sodium (%)	0.24	0.25	0.26
Lysine (%)	1.52	1.30	1.17
Methionine (%)	0.71	0.62	0.55
Methionine + Cysteine (SAA) (%)	1.11	0.97	0.88
Total phosphorus (%)	0.82	0.77	0.73
Available phosphorus (%)	0.47	0.45	0.43
Analyzed Composition[5]			
Crude protein (%)	25.28	20.91	18.78
Crude fat (%)	5.88	4.75	5.74
Calcium (%)	1.04	2.71	1.17
Sodium (%)	0.20	0.13	0.13
Lysine (%)	1.76	1.15	1.19
Methionine (%)	1.32	0.38	0.47
Methionine + Cysteine (SAA) (%)	0.99	0.65	0.77
Total phosphorus (%)	0.8 2	0.92	0.9 8

[1]Vitamin premix per kg of diet: vitamin A = 16435.29 IU; vitamin D3 = 3,582,452; 25-hydroxyvitamin D3 = 0.08 mg; vitamin E = 156.53 IU; vitamin B12 = 0.05 mg; biotin = 0.47 mg; menadione = 7.04 mg; thiamine 4.23 mg; riboflavin = 14.09 mg; d- pantothenate = 23.48 mg; vitamin B6 = 7.44 mg; niacin = 93.92 mg; folic acid = 3.13 mg; Trace mineral premix per ppm of diet: manganese = 113.59%; zinc = 107.90 %; iron = 10.22%; copper = 5.68%; iodine = 3.41%; cobalt = 1.70%; selenium = 0.34%

[2]Bacitracin Methylene Disalicylate, BMD 50 (Zoetis, Parsippany, NJ). `

[3]Salinomycin sodium, Saccox 60 (Huvepharma, Peachtree City, GA).

[4]Phase-fed basal diet formulation based on an industry-standard supplied by a commercial nutritionist.

[5]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus

International, Inc. Laboratory Services, St. Charles, MO).

Table A3. Ingredient composition and nutrient analyses of complete starter-phase test diets (as-fed) from 4 to 11 days of age (corn/dextrose, red/bronze, white/tan, and U.S. No. 2 Yellow) (%, as-fed basis).

	Starter Treatments			
	Corn/Dextrose	**Red/Bronze**	**White/Tan**	**U.S. No. 2 Yellow**
Ingredient (%)[1]				
Basal starter diet[2]	87.12	88.40	88.16	89.35
Grain sorghum	0.00	11.60	11.84	10.65
Dextrose	12.88	0.00	0.00	0.00
Calculated Composition[3]				
ME (kcal/kg)	3,066	3,035	3,000	3,000
Crude protein (%)	20.47	21.99	21.83	22.00
Crude fat (%)	5.11	5.50	5.45	5.52
Calcium (%)	1.16	1.18	1.17	1.19
Sodium (%)	0.19	0.19	0.19	0.20
Lysine (%)	1.20	1.24	1.24	1.23
Methionine (%)	0.59	0.62	0.62	0.63
Methionine + Cysteine (SAA) (%)	0.91	0.97	0.96	0.97
Total phosphorus (%)	0.71	0.76	0.76	0.76
Available phosphorus (%)	0.46	0.48	0.48	0.49
Analyzed Composition[4]				
Crude protein (%)	21.87	21.48	24.18	22.32
Crude fat (%)	7.50	5.80	5.43	5.63
Calcium (%)	0.99	0.82	1.18	0.77
Sodium (%)	0.19	0.16	0.21	0.16
Lysine (%)	1.46	1.33	1.65	1.46
Methionine (%)	0.64	0.58	0.65	0.62
Methionine + Cysteine (SAA) (%)	0.92	0.88	0.96	0.91
Total phosphorus (%)	0.72	0.72	0.83	0.73

[1,2,3]Phase-fed basal diet (Table 2.) and complete diet formulation based on an industry-standard supplied by a commercial nutritionist.
[4]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

Table A4. Ingredient composition, nutrient analyses and calculated treatment AME_n of complete grower-phase test diets (as-fed) from 12 to 24 days of age (corn/dextrose, red/bronze, white/tan, and U.S. No. 2 Yellow) (%, as-fed basis).

	Grower Treatments			
	Corn/Dextrose	**Red/Bronze**	**White/Tan**	**U.S. No. 2 Yellow**
Ingredient (%)[1]				
Basal grower diet[2]	85.04	86.54	86.30	86.18
Grain sorghum	0.00	13.46	13.70	13.82
Dextrose	14.96	0.00	0.00	0.00
Calculated $AME_{n\ treatment}$ (DM, kcal/kg)[3]	3,236	3,294	3,285	3,144
Calculated Composition[4]				
ME (kcal/kg)	3,126	3,090	3,050	3,052
Crude protein (%)	17.10	18.80	18.63	18.62
Crude fat (%)	4.64	5.07	5.03	5.06
Calcium (%)	1.05	1.06	1.06	1.06
Sodium (%)	0.20	0.20	0.20	0.20
Lysine (%)	1.01	1.05	1.05	1.05
Methionine (%)	0.50	0.54	0.53	0.53
Methionine + Cysteine (SAA) (%)	0.78	0.85	0.84	0.84
Total phosphorus (%)	0.66	0.71	0.71	0.71
Available phosphorus (%)	0.43	0.45	0.45	0.45
Analyzed Composition[5]				
Crude protein (%)	19.91	19.39	19.47	19.60
Crude fat (%)	4.57	4.67	5.01	4.91
Calcium (%)	1.69	1.93	1.58	1.91
Sodium (%)	0.18	0.19	0.17	0.17
Lysine (%)	1.10	1.15	1.09	1.12
Methionine (%)	0.48	0.47	0.48	0.46
Methionine + Cysteine (SAA) (%)	0.76	0.77	0.76	0.47
Total phosphorus (%)	0.90	0.96	0.95	0.94

[1,2,4]Phase-fed basal diet (Table 2.) and complete diet formulation based on an industry-standard supplied by a commercial nutritionist.
[3]Calculated AME_n of each complete test diet determined using equation *(1) Treatment AME_n*, (Macleod et al., 2008).
[5]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc Laboratory Services, St. Charles, MO).

Table A5. Ingredient composition, nutrient and calculated treatment AME_n of complete finisher-phase test diets (as-fed) from 25 to 47 days of age (corn/dextrose, red/bronze, white/tan, and U.S. No. 2 Yellow) (%, as-fed basis).

	Finisher Treatments			
	Corn/Dextrose	**Red/Bronze**	**White/Tan**	**U.S. No. 2 Yellow**
Ingredient (%)[1]				
Basal finisher diet[2]	84.06	85.66	85.40	85.27
Grain sorghum	0.00	14.35	14.61	14.74
Dextrose	15.95	0.00	0.00	0.00
Calculated $AME_{n\ treatment}$ (DM, kcal/kg)[3]	3,359	3,440	3,469	3,519
Calculated Composition[4]				
ME (kcal/kg)	3,207	3,171	3,127	3,130
Crude protein (%)	15.26	17.05	16.88	16.87
Crude fat (%)	5.09	5.56	5.51	5.54
Calcium (%)	0.96	0.98	0.98	0.98
Sodium (%)	0.20	0.20	0.20	0.20
Lysine (%)	0.89	0.94	0.94	0.94
Methionine (%)	0.45	0.48	0.48	0.48
Methionine + Cysteine (SAA) (%)	0.70	0.77	0.76	0.76
Total phosphorus (%)	0.62	0.67	0.67	0.67
Available phosphorus (%)	0.40	0.43	0.42	0.42
Analyzed Composition[5]				
Crude protein (%)	17.48	17.98	18.54	17.37
Crude fat (%)	4.98	5.50	5.79	5.55
Calcium (%)	1.12	1.16	1.20	1.23
Sodium (%)	0.17	0.17	0.21	0.19
Lysine (%)	1.03	1.06	1.10	1.03
Methionine (%)	0.37	0.46	0.46	0.42
Methionine + Cysteine (SAA) (%)	0.63	0.72	0.73	0.69
Total phosphorus (%)	0.92	0.85	0.91	0.88

[1,2,4]Phase-fed basal diet (Table 2.) and complete diet formulation based on an industry-standard supplied by a commercial nutritionist.
[3]Calculated AME_n of each complete test diet determined using equation *(1) Treatment AME_n*, (Macleod et al., 2008).
[5]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

Objective 2.

Table A6. Ingredient composition of basal Bobwhite quail diet (as-fed) from a 1 to 84 day grow-out for complete test diets.

	Starter/Grower (1-84 d)
Ingredient (%)	
Corn	35.00
Soybean meal, 47.5% CP	52.80
Fat, vegetable	7.84
Mono-dicalcium phosphate	2.37
Limestone	0.57
Sodium chloride	0.44
DL-methionine	0.50
Choline chloride, 60%	0.25
Vitamin and trace mineral premix[1]	0.19
BMD 50[2]	0.05
Calculated AME$_{n\ treatment}$ (DM, kcal/kg)[3]	2,884
Calculated Composition (%)	
ME (kcal/kg)	3,127
Crude Protein	28.08
Calcium	1.06
Sodium	0.19
Lysine	1.55
Methionine	0.85
Methionine + Cysteine (SAA)	1.25
Total phosphorous	1.11
Available phosphorus	0.58

[1]Commercial vitamin and trace mineral premix for turkeys.
[2]Bacitracin Methylene Disalicylate, BMD 50 (Zoetis, Parsippany, NJ).

Table A7. Ingredient composition and nutrient analyses of complete starter/grower Bobwhite quail test diets from 4 to 84 days of age (corn/dextrose, red/bronze, white/tan and U.S. No. 2 yellow) (%, as-fed basis).

	Starter/Grower Treatments			
	Corn/Dextrose	Red/Bronze	White/Tan	U.S. No. 2 Yellow
Ingredient (%)[1]				
Basal starter/grower[2]	89.85	92.21	92.26	91.92
Grain sorghum	0.00	7.79	7.74	8.08
Dextrose	10.15	0.00	0.00	0.00
Calculated $AME_{n\ treatment}$ (DM, kcal/kg)[3]	4,013	3,919	3,618	3,950
Calculated Composition[4] **(%)**				
ME (kcal/kg)	3,234	3,209	3,185	3,186
Crude protein	26.31	27.81	27.74	27.67
Crude fat	8.74	9.17	9.15	9.14
Calcium	0.63	0.65	0.65	0.65
Sodium	0.18	0.18	0.19	0.18
Lysine	1.50	1.55	1.56	1.55
Methionine	0.83	0.87	0.87	0.86
Methionine + Cysteine (SAA)	1.22	1.29	1.28	1.28
Total phosphorus	0.84	0.88	0.88	0.88
Available phosphorus	0.58	0.60	0.60	0.60
Analyzed Composition[5] **(%)**				
Crude protein	26.87	26.42	26.86	25.46
Crude fat	7.50	7.15	6.75	6.75
Calcium	0.98	0.83	0.89	0.96
Sodium	0.13	0.10	0.10	0.12
Lysine	1.28	1.31	1.42	1.37
Methionine	1.07	0.84	0.92	0.91
Methionine + Cysteine (SAA)	1.40	1.18	1.28	1.28
Total phosphorus	1.07	0.90	0.95	1.04

[1,2,4]Phase-fed basal diet (Table 1.) and complete diet formulation based on an industry-standard supplied by a commercial nutritionist.
[3]Calculated AME_n of each complete test diet determined using equation *(1) Treatment AME_n*, (Macleod et al., 2008).
[5]Proximate analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

Objective 3.

Table A8. Nutrient and gross energy analyses of sources of corn and modern varieties of grain sorghum (red/bronze, white/tan, U.S. No. 2 yellow, and mixed).

		Grain Sorghum Variety			
	Corn	**Red/Bronze**	**White/Tan**	**U.S. No. 2 Yellow**	**Mixed**
Proximates (%)[1]					
Dry matter	84.58	87.48	89.93	84.44	85.73
GE, as-fed (kcal/kg)[2]	3,926	3,752	3,686	3,653	---
Ash	1.07	0.90	1.10	1.39	1.35
Crude fat	3.13	2.89	2.46	2.93	2.57
Crude fiber	1.50	1.80	1.70	2.20	1.90
Crude protein	7.52	8.87	9.33	8.65	8.83
Methionine	0.15	0.15	0.17	0.14	0.15
Lysine	0.26	0.24	0.24	0.23	0.22
Threonine	0.26	0.30	0.31	0.28	0.30

[1]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).
[2]Determined by University of Georgia Feed, Environmental and Water (FEW) Laboratory (Athens, GA).

Table A9. Ingredient composition of basal Japanese quail diet (as-fed) from a 1 to 39 day grow-out for complete test diets.

	Starter/Grower (1-39 d)
Ingredient (%)	
Corn	34.61
Soybean meal, 47.5% CP	50.86
Fat, vegetable	8.15
Mono-dicalcium phosphate	2.79
Limestone	1.27
Sodium chloride	0.45
DL-methionine	0.55
L-threonine	0.18
Biolys	0.58
Choline chloride, 60%	0.27
Vitamin and trace mineral premix[1]	0.19
Copper sulfate (5 H2O)	0.05
Saccox 60[2]	0.05
Calculated $AME_{n\ treatment}$ (DM, kcal/kg)[3]	2,874
Calculated Composition (%)	
ME (kcal/kg)	3,120
Crude Protein	27.60
Calcium	1.38
Sodium	0.20
Lysine	1.79
Methionine	0.90
Methionine + Cysteine (SAA)	1.28
Total phosphorous	1.17
Available phosphorus	0.65

[1]Vitamin and trace mineral premix: Zinc = 7.15%; Selenium = 172 ppm.

[2]Salinomycin sodium, Saccox 60 (Huvepharma, Peachtree City, GA).

Table A10. Ingredient composition and nutrient analyses of complete starter/grower Japanese quail test diets for from 4 to 39 days of age (corn/dextrose, red/bronze, white/tan and U.S. No. 2 yellow) (%, as-fed basis).

	Starter/Grower Treatments			
	Corn/Dextrose	**Red/Bronze**	**White/Tan**	**U.S. No. 2 Yellow**
Ingredient (%)[1]				
Basal starter/grower[2]	90.89	92.75	92.79	92.71
Grain sorghum	0.00	7.25	7.21	7.29
Dextrose	9.10	0.00	0.00	0.00
Calculated $AME_{n\ treatment}$ (DM, kcal/kg)[3]	3,715	3,795	3,608	3,568
Calculated Composition[4] **(%)**				
ME (kcal/kg)	3,198	3,176	3,154	3,154
Crude protein	25.85	27.13	27.06	27.05
Crude fat	9.07	9.45	9.43	9.44
Calcium	0.94	0.96	0.96	0.96
Sodium	0.19	0.19	0.19	0.19
Lysine	1.77	1.82	1.82	1.82
Methionine	0.87	0.91	0.90	0.90
Methionine + Cysteine (SAA)	1.26	1.31	1.31	1.31
Total phosphorus	0.91	0.95	0.95	0.96
Available phosphorus	0.66	0.68	0.68	0.68
Analyzed Composition[5] **(%)**				
Crude protein	26.97	27.76	28.03	29.22
Crude fat	8.34	8.84	7.83	8.74
Calcium	1.12	1.07	1.11	0.97
Sodium	0.15	0.12	0.15	0.10
Lysine	2.26	2.20	2.14	2.10
Methionine	1.01	0.92	1.01	0.88
Methionine + Cysteine (SAA)	1.42	1.35	1.42	1.30
Total phosphorus	0.82	0.86	0.88	0.84

[1,2,4]Phase-fed basal diet (Table 2.) and complete diet formulation based on an industry-standard supplied by a commercial nutritionist.
[3]Calculated AME_n of each complete test diet determined using equation *(1) Treatment AME_n*, (Macleod et al., 2008).
[5]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

Objective 4.

Table A11. Nutrient analyses of sources of corn and modern varieties of grain sorghum (red/bronze, white/tan, U.S. No. 2 yellow).

		Grain Sorghum Variety		
	Corn	**Red/Bronze**	**White/Tan**	**U.S. No. 2 Yellow**
Proximates (%)				
Dry matter	88.34	82.75	88.97	87.86
Ash	1.04	1.01	1.04	1.15
Crude fat	3.52	2.46	2.36	2.60
Crude fiber	2.30	1.90	2.40	2.90
Crude protein	7.00	8.94	9.38	9.38
Methionine	0.17	0.16	0.20	0.17
Lysine	0.25	0.20	0.22	0.22
Threonine	0.27	0.30	0.32	0.32

[1]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

Table A12. Ingredient composition and calculated/analyzed energy and nutrient composition of starter diet with respective test ingredient: corn or red/bronze, white/tan, U.S. No. 2 Yellow grain sorghum (as-fed) from 1 to 14 d-of-age.

	Starter Treatments[1]			
	S	RB	WT	Y
Ingredient (%)				
Corn	56.85	0.00	0.00	0.00
Red/Bronze grain sorghum	0.00	60.39	0.00	0.00
White/Tan grain sorghum	0.00	0.00	56.12	0.00
U.S. No. 2 Yellow grain sorghum	0.00	0.00	0.00	56.32
Soybean meal, 47.5% CP	38.25	35.60	36.52	36.51
Fat, vegetable	2.32	1.29	4.63	4.45
Defluorinated phosphate	0.90	0.84	0.87	0.85
Limestone	0.14	0.25	0.20	0.22
Sodium chloride	0.43	0.43	0.43	0.43
DL-methionine	0.33	0.31	0.35	0.34
L-threonine	0.05	0.05	0.06	0.06
L-lysine	0.13	0.24	0.21	0.22
Choline chloride, 60%	0.16	0.16	0.16	0.16
Vitamin premix[2]	0.25	0.25	0.25	0.25
Trace minerals[3]	0.08	0.08	0.08	0.08
Phytase[4]	0.01	0.01	0.01	0.01
Sacox 60[5]	0.05	0.05	0.05	0.05
BMD 50[6]	0.05	0.05	0.05	0.05
Calculated Composition (%)				
ME (kcal/kg)	3,031	3,031	3,031	3,031
Crude protein	22.38	23.55	22.95	22.96
Crude fat	4.83	3.35	6.40	6.37
Calcium	0.90	0.90	0.90	0.90
Sodium	0.21	0.21	0.21	0.21
Lysine	1.37	1.36	1.36	1.36
Methionine	0.66	0.66	0.66	0.66
Methionine + Cysteine (SAA)	1.01	1.02	1.02	1.02
Total phosphorus	0.58	0.57	0.56	0.57
Available phosphorus	0.43	0.43	0.43	0.43
Analyzed Composition (%)[7]				
Crude protein	22.75	21.81	21.00	22.06
Crude fat	4.21	3.03	6.16	6.29
Calcium	0.62	0.58	0.54	0.61
Sodium	0.15	0.15	0.16	0.18
Lysine	1.25	1.23	1.20	1.30
Methionine	0.82	0.73	0.77	0.80
Methionine + Cysteine (SAA)	1.15	1.04	1.06	1.12
Total phosphorus	0.58	0.58	0.56	0.58

[1] Treatment abbreviations: S = standard (corn control); RB = red/bronze; WT = white/tan; Y= U.S. No. 2 Yellow.
[2] Supplied per kg of diet: thiamin•mononitrate, 2.4 mg; nicotinic acid, 44 mg; riboflavin, 4.4 mg; D-Ca pantothenate, 12 mg; vitamin B_{12} (cobalamin),12.0 µg; pyridoxine•HCL, 4.7 mg; D-biotin, 0.11 mg; folic acid, 5.5 mg; menadione sodium bisulfite complex, 3.34 mg; choline chloride, 220 mg; cholecalciferol, 27.5 ug; trans-retinyl acetate, 1,892 ug; all-rac α tocopheryl acetate, 11 mg; ethoxyquin, 125 mg.
[3] Supplied per kg of diet: manganese ($MnSO_4$•H_2O), 60 mg; iron ($FeSO_4$•$7H_2O$), 30 mg; zinc (ZnO), 50 mg; copper ($CuSO_4$•$5H_2O$), 5 mg; iodine (ethylene diamine dihydroiodide), 0.15 mg; selenium ($NaSe0_3$), 0.3 mg.
[4] Quantum Blue phytase (A.B. Vista, Marlborough, Wiltshire).
[5] Bacitracin Methylene Disalicylate, BMD 50 (Zoetis, Parsippany, NJ).
[6] Salinomycin sodium, Sacox 60 (Huvepharma, Peachtree City, GA).
[7] Proximate analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

Table A13. Ingredient composition and calculated/analyzed energy and nutrient composition of grower diet with respective test ingredient: corn or red/bronze, white/tan, U.S. No. 2 Yellow grain sorghum (as-fed) from 15 to 28 d-of-age.

	Grower Treatments[1]			
	S	RB	WT	Y
Ingredient (%)				
Corn	56.85	0.00	0.00	0.00
Red/Bronze grain sorghum	0.00	60.39	0.00	0.00
White/Tan grain sorghum	0.00	0.00	56.12	0.00
U.S. No. 2 Yellow grain sorghum	0.00	0.00	0.00	56.32
Soybean meal, 47.5% CP	38.25	35.60	36.52	36.51
Fat, vegetable	2.32	1.29	4.63	4.45
Defluorinated phosphate	0.90	0.84	0.87	0.85
Limestone	0.14	0.25	0.20	0.22
Sodium chloride	0.43	0.43	0.43	0.43
DL-methionine	0.33	0.31	0.35	0.34
L-threonine	0.05	0.05	0.06	0.06
L-lysine	0.13	0.24	0.21	0.22
Choline chloride, 60%	0.16	0.16	0.16	0.16
Vitamin premix[2]	0.25	0.25	0.25	0.25
Trace minerals[3]	0.08	0.08	0.08	0.08
Phytase[4]	0.01	0.01	0.01	0.01
Sacox 60[5]	0.05	0.05	0.05	0.05
BMD 50[6]	0.05	0.05	0.05	0.05
Calculated Composition (%)				
ME (kcal/kg)	3,086	3,086	3,086	3,086
Crude protein	19.14	20.94	20.26	20.28
Crude fat	4.54	3.03	6.46	6.43
Calcium	0.85	0.85	0.85	0.85
Sodium	0.22	0.22	0.22	0.22
Lysine	1.16	1.16	1.16	1.16
Methionine	0.57	0.56	0.57	0.57
Methionine + Cysteine (SAA)	0.88	0.89	0.89	0.89
Total phosphorus	0.53	0.53	0.52	0.53
Available phosphorus	0.40	0.40	0.40	0.40
Analyzed Composition (%)[7]				
Crude protein	20.94	21.00	20.31	19.88
Crude fat	4.14	2.59	6.09	5.66
Calcium	0.62	0.49	0.65	0.59
Sodium	0.15	0.16	0.23	0.16
Lysine	1.02	1.11	1.05	1.11
Methionine	0.73	0.73	0.70	0.90
Methionine + Cysteine (SAA)	1.01	1.02	0.98	1.17
Total phosphorus	0.54	0.50	0.60	0.54

[1] Treatment abbreviations: S = standard (corn control); RB = red/bronze; WT = white/tan; Y= U.S. No. 2 Yellow.
[2] Supplied per kg of diet: thiamin•mononitrate, 2.4 mg; nicotinic acid, 44 mg; riboflavin, 4.4 mg; D-Ca pantothenate, 12 mg; vitamin B_{12} (cobalamin),12.0 µg; pyridoxine•HCL, 4.7 mg; D-biotin, 0.11 mg; folic acid, 5.5 mg; menadione sodium bisulfite complex, 3.34 mg; choline chloride, 220 mg; cholecalciferol, 27.5 ug; trans-retinyl acetate, 1,892 ug; all-rac α tocopheryl acetate, 11 mg; ethoxyquin, 125 mg.
[3] Supplied per kg of diet: manganese ($MnSO_4 \cdot H_2O$), 60 mg; iron ($FeSO_4 \cdot 7H_2O$), 30 mg; zinc (ZnO), 50 mg; copper ($CuSO_4 \cdot 5H_2O$), 5 mg; iodine (ethylene diamine dihydroiodide), 0.15 mg; selenium ($NaSe0_3$), 0.3 mg.
[4] Quantum Blue phytase (A.B. Vista, Marlborough, Wiltshire).
[5] Bacitracin Methylene Disalicylate, BMD 50 (Zoetis, Parsippany, NJ).
[6] Salinomycin sodium, Sacox 60 (Huvepharma, Peachtree City, GA).
[7] Proximate analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

Table A14. Ingredient composition and calculated/analyzed energy and nutrient composition of finisher diet with respective test ingredient: corn or red/bronze, white/tan, U.S. No. 2 Yellow grain sorghum (as-fed) from 29 to 42 d-of-age.

	Finisher Treatments[1]			
	S	RB	WT	Y
Ingredient (%)				
Corn	69.49	0.00	0.00	0.00
Red/Bronze grain sorghum	0.00	71.59	0.00	0.00
White/Tan grain sorghum	0.00	0.00	66.54	0.00
U.S. No. 2 Yellow grain sorghum	0.00	0.00	0.00	66.76
Soybean meal, 47.5% CP	25.75	24.56	25.66	25.64
Fat, vegetable	2.32	1.37	5.32	5.11
Defluorinated phosphate	0.70	0.62	0.65	0.62
Limestone	0.37	0.47	0.41	0.44
Sodium chloride	0.48	0.49	0.48	0.49
DL-methionine	0.23	0.20	0.24	0.24
L-threonine	0.05	0.02	0.03	0.03
L-lysine	0.14	0.21	0.18	0.18
Choline chloride, 60%	0.10	0.10	0.10	0.10
Vitamin premix[2]	0.25	0.25	0.25	0.25
Trace minerals[3]	0.08	0.08	0.08	0.08
Phytase[4]	0.01	0.01	0.01	0.01
BMD 50[6]	0.05	0.05	0.05	0.05
Calculated Composition (%)				
ME (kcal/kg)	3,164	3,164	3,164	3,164
Crude protein	17.32	19.39	18.68	18.70
Crude fat	5.10	3.57	7.18	7.15
Calcium	0.80	0.80	0.80	0.80
Sodium	0.22	0.22	0.22	0.22
Lysine	1.04	1.04	1.04	1.04
Methionine	0.51	0.50	0.51	0.51
Methionine + Cysteine (SAA)	0.80	0.81	0.81	0.81
Total phosphorus	0.49	0.49	0.48	0.49
Available phosphorus	0.38	0.38	0.38	0.38
Analyzed Composition (%)[7]				
Crude protein	17.44	17.62	19.19	19.44
Crude fat	4.31	3.31	7.85	6.68
Calcium	0.55	0.48	0.58	0.46
Sodium	0.20	0.17	0.20	0.12
Lysine	0.88	0.94	1.02	0.96
Methionine	0.64	0.64	0.60	0.56
Methionine + Cysteine (SAA)	0.87	0.88	0.88	0.83
Total phosphorus	0.45	0.44	0.54	0.48

[1] Treatment abbreviations: S = standard (corn control); RB = red/bronze; WT = white/tan; Y= U.S. No. 2 Yellow.
[2] Supplied per kg of diet: thiamin•mononitrate, 2.4 mg; nicotinic acid, 44 mg; riboflavin, 4.4 mg; D-Ca pantothenate, 12 mg; vitamin B_{12} (cobalamin),12.0 µg; pyridoxine•HCL, 4.7 mg; D-biotin, 0.11 mg; folic acid, 5.5 mg; menadione sodium bisulfite complex, 3.34 mg; choline chloride, 220 mg; cholecalciferol, 27.5 ug; trans-retinyl acetate, 1,892 ug; all-rac α tocopheryl acetate, 11 mg; ethoxyquin, 125 mg.
[3] Supplied per kg of diet: manganese ($MnSO_4 \cdot H_2O$), 60 mg; iron ($FeSO_4 \cdot 7H_2O$), 30 mg; zinc (ZnO), 50 mg; copper ($CuSO_4 \cdot 5H_2O$), 5 mg; iodine (ethylene diamine dihydroiodide), 0.15 mg; selenium ($NaSe0_3$), 0.3 mg.
[4] Quantum Blue phytase (A.B. Vista, Marlborough, Wiltshire).
[5] Bacitracin Methylene Disalicylate, BMD 50 (Zoetis, Parsippany, NJ).
[6] Salinomycin sodium, Sacox 60 (Huvepharma, Peachtree City, GA).
[7] Proximate analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

Objective 6.

Table A15. Ingredient and nutrient composition of starter/grower Japanese quail treatments (%, as-fed) for *Experiment 2* growth performance 1 to 39 d of age.

	Starter/Grower (1 – 39 d) Treatments[1]				
	C	**RB**	**WT**	**Y**	**M**
Ingredient (%)					
Corn	42.00	0.00	0.00	0.00	0.00
Grain sorghum	0.00	43.02	41.62	38.09	40.81
Soybean meal, 47.5%	46.00	46.00	46.00	47.00	46.00
Fat, vegetable	6.85	6.26	7.67	9.83	7.99
Mono-dicalcium phosphate	1.70	1.70	1.69	1.69	1.69
Limestone	1.13	1.14	1.14	1.11	1.13
Biolys	0.54	0.62	0.63	0.58	0.63
Sodium chloride	0.40	0.42	0.41	0.41	0.42
DL-methionine	0.50	0.52	0.53	0.54	0.53
L-threonine	0.20	0.20	0.20	0.20	0.20
Choline chloride, 60%	0.25	0.25	0.25	0.25	0.25
Vitamin and trace mineral premix[2]	0.18	0.18	0.18	0.18	0.18
Copper Sulfate (5 H2O)	0.05	0.05	0.05	0.05	0.05
Saccox 60[3]	0.04	0.04	0.04	0.04	0.04
Phytase[4]	0.03	0.03	0.03	0.03	0.03
Calculated Composition (%)					
ME (kcal/kg)	3,142	3,142	3,142	3,142	3,142
Crude Protein	26.00	26.00	26.13	26.08	26.08
Crude fat	8.85	7.87	9.16	11.34	9.52
Calcium	1.26	1.26	1.26	1.26	1.26
Sodium	0.18	0.18	0.18	0.18	0.18
Lysine	1.66	1.66	1.66	1.66	1.66
Methionine	0.83	0.84	0.85	0.85	0.85
Methionine + Cysteine (SAA)	1.20	1.20	1.20	1.20	1.20
Total Phosphorus	0.92	0.92	0.92	0.93	0.92
Available Phosphorus	0.60	0.60	0.60	0.60	0.60
Analyzed Composition (%)[5]					
Crude Protein	26.34	26.56	26.70	27.10	26.05
Crude Fat	8.78	6.86	7.48	7.19	8.76
Calcium	1.29	0.94	0.87	1.07	0.70
Sodium	0.13	0.13	0.06	0.10	0.03
Lysine	1.87	2.03	1.85	1.85	1.82
Methionine	0.94	1.02	0.87	0.93	0.84
Methionine + Cysteine (SAA)	1.28	1.37	1.23	1.28	1.18
Total Phosphorus	0.89	0.82	0.74	0.84	0.55

[1]Treatment abbreviations: C = corn; RB = red/bronze; WT = white/tan; Y= U.S. No. 2 Yellow; M = mixed.
[2]Vitamin and trace mineral premix: Zinc = 7.15%; Selenium = 172 ppm.
[3]Salinomycin sodium, Saccox 60 (Huvepharma, Peachtree City, GA).
[4]Ronozyme, HiPhos (DSM, Nutritional Products, LLC, Kingstree, SC).
[5]Proximate Analysis was determined using the AOAC (Association of Official Analytical Chemists) method (Novus International, Inc. Laboratory Services, St. Charles, MO).

List of Presentations and Publications

Presentations:

A.H. Moritz, S.K. Krombeen, R.E. Buresh, M.E. Blair, R.M. Kaminski, W.C. Bridges, M. Arguelles-Ramos, T.A. Wilmoth. 2021. Apparent metabolizable energy and performance of broilers and Japanese quail fed selected modern grain sorghum varieties. Poultry Science Association Annual Meeting, *Virtual*.

A.H. Moritz, M. E. Blair, R. E. Buresh, W. C. Bridges, M. Arguelles-Ramos. 2021. Effect of select modern grain sorghum varieties on the growth performance and carcass traits of broiler chickens. Poultry Science Association Annual Meeting, *Virtual*.

A.H. Moritz, S.K. Krombeen, R.E. Buresh, M.E. Blair, R.M. Kaminski, W.C. Bridges, T.A. Wilmoth. 2020. Growth performance and carcass traits of broilers and Japanese quail fed selected modern varieties of grain sorghum. International Poultry Scientific Forum, Atlanta, GA.

A.H. Moritz, S.K. Krombeen, R.E. Buresh, M.E. Blair, W.C. Bridges, T.A. Wilmoth. 2019. Apparent metabolizable energy value of selected modern grain sorghum varieties for feeding commercial broilers. Poultry Science Association Annual Meeting, Montreal, Quebec, CA.

Publications:

Apparent metabolizable energy and performance of broilers fed selected grain sorghum varieties A. H. Moritz, S. K. Krombeen, M. E. Blair, R. E. Buresh, R. M. Kaminski,
W. C. Bridges, M. Arguelles-Ramos, T. A. Wilmoth
Submitted to Journal of Applied Poultry Research; in-progress for submission to Animal Nutrition

Apparent metabolizable energy, growth performance and carcass traits of Japanese quail fed selected modern grain sorghum varieties
A. H. Moritz, M. Motallebi, S. K. Krombeen, M. E. Blair, R. E. Buresh,
R. M. Kaminski, W. C. Bridges, M. Arguelles-Ramos, T. A. Wilmoth
In-progress for submission to Animal Bioscience

Effect of select modern grain sorghum varieties on the growth performance and carcass traits of broiler chickens
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List of Abbreviations

Abbreviation	
ADG	Average daily gain
Adj.FCR	Adjusted feed conversion ratio
AME_n	Nitrogen corrected apparent metabolizable energy
BCR	Benefit-cost ratio
BrW	Breast weight
BrY	Breast yield
B.W.	Body weight
C	Corn-based diet
C.Y.	Carcass yield
FCR	Feed conversion ratio
FEW	University of Georgia Feed, Environmental and Water
F.I.	Feed intake
GE	Gross energy
GEE	gross energy output in excreta
GEI	Gross energy intake
HCW	Hot carcass weight
kcal	kilocalories
kg	kilogram
LBW	Live body weight
M	Sorghum Mix
NE	Nitrogen output from excreta
R.B.	Red/bronze sorghum-based diet
SE	Southeastern
USCP	United Sorghum Checkoff Program
WT	White/tan sorghum-based diet
Y	Yellow No.2 sorghum-based diet