

Running head: Sorghum particle size for broilers

**Impact of U.S. sorghum particle size on feed characteristics, and growth performance,
gizzard weight and pH in broiler chickens¹**

Victoria C Wilson*, Haley K. Otott*, Julia G. Pezzalli*, Brian. J. Kerr[◇] and Chad B. Paulk*²

*Department of Grain Science and Industry, College of Agriculture, Kansas State University,
Manhattan, KS, USA, 66506

[◇] USDA Agriculture Research Service-National Laboratory for Agriculture and Environment;
Ames, IA 50011

Keywords: sorghum, particle size, gizzards, growth, broilers

¹ Appreciation is expressed to the United Sorghum Checkoff Program for financial support of this project.

² Corresponding author: cpaulk@ksu.edu

SUMMARY

Sorghum serves as an energy source in broiler diets when it is competitively priced for feed formulation. The objective of this study was to evaluate U.S. sorghum particle size (mean geometric diameter, d_{gw}) effects on growth performance, gizzard weight, and pH in broilers from 4-49 days of age. A floor pen study was conducted with a treatment structure of 850 μm for corn and 414, 606, 821, 1046, and 1124 μm for the sorghum treatments. Body weight gain (**BWG**), feed intake (**FI**), and calculated feed conversion ratio (**FCR**) adjusted for mortality were determined for 4-phases. On d 49, two average body weight birds per pen were selected for determination of gizzard pH and weight. Overall (days 4-49) birds fed sorghum-based diets had increased ($P < 0.05$) BWG and FI compared to those fed the corn-based diets, resulting in no evidence of difference in FCR. Increasing sorghum particle size tended to increase (linear, $P = 0.059$) FI and BWG (quadratic, $P = 0.056$) of broilers, with the majority of the improvements in BWG occurring when sorghum d_{gw} was increased from 1000 to 1200 μm . Increasing sorghum d_{gw} up to 1000 μm increased relative gizzard weight (quadratic, $P < 0.01$). In conclusion, broilers fed the sorghum-based diets had increased BWG and FI compared to those fed the corn-based diets with no evidence of difference in FCR. Based on the design of this experiment, targeting a coarser particle size in the 1,000 - 1,200 μm range was optimal for growth performance and gizzard development.

DESCRIPTION OF THE PROBLEM

Sorghum is a cereal grain that can potentially replace corn in broiler diets, particularly in regions where it is more readily available or cost-effective. Although the nutritional content of sorghum is similar to that of corn, sorghum traditionally contained tannins which reduce the nutritional value when fed to broilers (Gualtieri and Rapaccini, 1990). Tannin-containing sorghum reduces broiler growth performance due to decreased nutrient digestibility whereas low-tannin or tannin-free sorghum have been reported to have similar feeding values to that of corn (Selle et al. 2010; Moritz et al. 2022). In 2025, a total of 91 sorghum samples from the U.S. were tested and confirmed to have less than 4.0 mg CE/g, implying an absence of detectable tannins. This was consistent with tannin survey results from 2023 and 2024 (U.S. Grains Council 2025). Therefore, current tannin-free sorghum should be able to replace corn in broiler diets without negatively affecting performance.

When manufacturing broiler diets, nutritionist must determine the target cereal grain particle size. Grain particle size (geometric mean diameter; d_{gw}) influences the development and physiology of the digestive tract. Specifically, the gizzard is responsible for mechanical grinding and the initiation of nutrient digestion. Gizzard development and activity are influenced by the physical characteristics of the diet, especially feed d_{gw} . A more active gizzard, typically associated with coarser feed, often exhibits a lower pH, which may contribute to improved pathogen control and nutrient digestibility. Coarser corn particles ($>600 \mu\text{m}$) enhance gizzard muscularity and have been linked to increased feed retention time and lower digesta pH (Xu et al. 2015b; Naderinejad et al. 2016). Previous research has suggested that dietary d_{gw} modulates gizzard pH, likely due to its effects on fermentation activity and acid secretion (Ghasemi-

Aghgonbad et al. 2024). On the other hand, finely ground particles reduce gizzard activity, alter digesta pH, and accelerate passage rate, potentially limiting nutrient absorption (Svihus 2011).

Original research on sorghum particle size determined that grinding sorghum to 300 μm optimized feed conversion ratio (**FCR**) in broilers (Healy et al. 1991). However, limited research on the effects of sorghum particle size has been conducted since. Recent research has determined that whole sorghum can be added to broiler diets with no negative impacts on growth performance compared to ground sorghum or corn (Fernandes et al. 2013). Similar to the response of feeding coarsely ground corn, it is hypothesized that there would be no negative impact of increasing sorghum d_{gw} on growth performance and that gizzard weight would increase and gizzard contents pH would decrease with increasing sorghum particle size. Therefore, the objective of this experiment was to determine the influence of U.S. sorghum d_{gw} on growth performance, gizzard weight and gizzard digesta pH in broiler chickens.

MATERIALS AND METHODS

Animal care and management

This experiment was conducted at the Kansas State University Poultry Unit in Manhattan, KS, using experimental protocols and methods approved by the Institutional Animal Care and Use Committee (4850-29520). A total of 864-day old COBB by-product breeders were allotted to 72 pens (n=12 broilers per pen). Broilers were placed on a common diet for the first 4 days. On day 4, pens were reduced to 10 broilers per pen. Pens were 96.5 \times 33 cm, and chicks were maintained in an environmentally control room with *ad libitum* access to feed (13.9 kg; Chore Time, Milford, IN) and water (Chore-Time Steadi-FLOW, Milford, IN). Dietary treatments were randomly assigned to pens within location block and balanced for average body

weight. Body weight gain (**BWG**) and feed intake (**FI**) data were collected for day 4-12, 13-28, 29-39, and 40-49 with feed conversion ratio (**FCR**) being calculated for each phase and adjusted for mortality. Light to dark period was set to follow industry recommendation of stair stepping from 24 hours light at d 0 to 18 hours light by day 6, adding 1 hour of dark each day until achieving 18 hours light and 6 hours dark from d 6-49 of the trial.

On day 49, average pen BW was calculated, and 2 broilers of approximate average pen BW were selected and euthanized via CO₂ asphyxiation for the collection of gizzard content acidity (**pH**) and relative organ weight (**RGW**). Gizzard contents pH was measured utilizing a portable pH and temperature meter (HI99165, Hanna Instruments, Woonsocket, RI) prior to cleaning out the organ. The probe was inserted in such a manner that it was ensured to not be touching any organ wall while measuring the digesta pH. After pH was determined, the gizzard was trimmed of excess connective tissue, gizzard contents were removed, and gizzards were rinsed with distilled water. Gizzards were weighed, and relative gizzard weights were reported as a ratio of gizzard weight to body weight.

Study design and particle size reduction

A single lot of corn and U.S. sorghum were sourced and used for the experiment. Grains were analyzed for mycotoxins, proximate analysis, and amino acid profiles (Table 1). Deoxynivalenol, aflatoxin and fumonisin were analyzed at ATC Scientific (North Little Rock, AR) where samples were extracted and isolated with an immunoaffinity column and analyzed on an HPLC-MS/MS. Proximate analysis and amino acid profiles (method 982.30 E [a, b, c]; AOAC, 2019) were completed for whole grain samples at the Agricultural Experiment Station Laboratories (University of Missouri, Columbia, MO). Proximate analysis included dry matter (method 930.15; AOAC, 2019), ash (method 942.05; AOAC, 2019), crude fiber (method 978.10;

AOAC, 2019), and crude fat (method 920.39; AOAC, 2019). Nitrogen was analyzed using the combustion method in a LECO analyzer (method 990.03; AOAC, 2019) with crude protein calculated as $N \times 6.25$.

Dietary treatments consisted of a corn-based (C; 800 μm) control diet and U.S. sorghum-based (S) diets with varying sorghum d_{gw} (400, 600, 800, 1000, 1200 μm). Target grain particle sizes were achieved using a 25-horsepower hammermill (Model 22115, Bliss Industries LLC, Ponca City, OK) equipped with 24 hammers. The chamber diameter measured 56 cm wide with a depth of 29 cm. The hammermill was equipped with a variable frequency drive (VFD), resulting in 3,560 rpm when operating at 100%.

To achieve each target d_{gw} , the hammer mill was set to a constant feeder rate of 15%. The hammer mill motor was equipped with a VFD which acts on the motor to slow the speed at which it rotates the shaft that turns the hammers. This directly affects tip speed. In brief, a known corn and sorghum particle size setting was utilized from previous research as the baseline settings for each grain. From there, screen size and VFD were manipulated to achieve target d_{gw} . Screen sizes utilized, VFD settings, and calculated tip speeds are recorded in Table 2 with the resulting d_{gw} and geometric standard deviation (S_{gw}). All ground grains needed for the experiment were produced in a single continuous run per treatment to ensure consistency of particle size throughout all dietary phases.

The d_{gw} and S_{gw} were determined according to the American Society of Agricultural and Biological Engineers (ASABE) method S319.4 (ASABE Standards, 2008). Analyses were conducted utilizing the 13-sieve stack with agitators and sieve agent, for 10 minutes in a Ro-Tap (ASAE S319.4 FEB 2008 R2012). In addition, flowability characteristics were measured using methodology outlined by (Kalivoda et al. 2017). Flowability parameters of ground grains were

measured in duplicate using compressibility, critical orifice (**COD**), and angle of repose (**AoR**), and these values were utilized to calculate the composite flow index (**CFI**).

Complete diet manufacturing

Ground cereal grains were used in diets that were manufactured at O. H. Kruse Feed Mill, Manhattan, KS. Diets were formulated to meet or exceed the recommendations set forth by Cobb Vantress for all nutrients. Diet formulations were balanced by standardized ileal digestible lysine, methionine, threonine, valine, total calcium, and digestible phosphorus. During formulation, sorghum and corn were assumed to be equal in metabolizable energy in order to keep added fat concentration the same between treatments. Diets were fed as Starter (days 4-12), Grower-1 (days 13-28), Grower-2 (days 29-39), and Finisher-1 (days 40-49). All treatments were mixed in a single batch utilizing a 907 kg twin shaft counterpoise mixer (Hayes and Stoltz, Model TRDB63-0152, Fort Worth, TX) and mash diets were steam conditioned (25 × 140 cm. Wenger twin shaft pre-conditioner, Model 150) and pelleted on a 1-ton 30-horsepower pellet mill (1012-2 HD Master Model, California Pellet Mill, Crawfordsville, IN) equipped with a 4.4 × 35 mm (length: diameter 8) pellet die. Prior to pelleting, the conditioner was set for an average conditioning retention time of 30 seconds. Pelleting production rate was 14.96 kg/min. Target conditioning temperature range was 82-85°C. Temperature readings were recorded three times per batch for conditioning temperature and hot pellet temperature. Pellets were cooled using a counter flow cooler (OP<>FLO™ AIR COOLER, Bliss Industries, Ponca City, OK) for 15 minutes prior to sampling and bagging. Starter diets were fed in crumble form utilizing a 23 x 15 cm single pair 3-horsepower roller mill (A24013, RMS, Harrisburg, SD). Grower-1, Grower-2, and Finisher-1 diets were fed as whole pellets. Cooled pellet samples were analyzed for pellet durability index (**PDI**) in triplicate for each batch of feed. The PDI was measured using the

Holeman 100 (Tekpro Limited, North Walsham, Norfolk, UK) set to 60 seconds on all treatments for all phases.

Statistical Analysis

Growth performance and gizzard data were analyzed as a randomized complete block design utilizing the general linear mixed procedure of SAS 9.4. Dietary treatment was considered the fixed effect, and pen location was the blocking factor. Dunnet's test was used to compare each sorghum treatment back to the corn control, and linear and quadratic contrast were utilized to determine the response to changing sorghum particle size. Results were considered significant at $P < 0.05$, and tendencies between $0.05 < P < 0.10$.

RESULTS AND DISCUSSION

Feed Quality Parameters

The d_{gw} , S_{gw} , particle size distribution, and flow ability metrics are reported in Table 3. The d_{gw} of all treatments, except for S1200, were within $\pm 50 \mu\text{m}$ of the target d_{gw} . The S1200 treatment resulted in a measured d_{gw} of 1124 μm . The S_{gw} for C800, S400, S600, S800, S1000, S1200 were 2.89, 2.89, 2.60, 2.69, 2.46, and 2.66 respectively. The S_{gw} represents the geometric distribution of different particles across screens in the sieve stack. Greater S_{gw} indicates a wider distribution of particle sizes, and a smaller S_{gw} indicates a tighter distribution. The sorghum 800 μm treatment had an S_{gw} of 2.69 compared to the corn S_{gw} of 2.89. The smaller sorghum S_{gw} resulted from less coarse particles (3.48% $>2360 \mu\text{m}$) compared to that of corn (11.62% $>2360 \mu\text{m}$). As the sorghum d_{gw} increased from 400 to 1000 μm , the S_{gw} decreased from 2.89 to 2.46. As the sorghum was ground to a smaller particle size, this resulted in more fines in the pan of the

sieve stack which led to an increase in S_{gw} . The S_{gw} of the sorghum ground to 1200 μm increased compared to the 1000 μm sorghum. This increase from 1000 to 1200 μm can be explained by a reduction of tip speed during grinding which is known to increase S_{gw} (Pfof, 1976). There was increase in coarse particles for the 1200 μm (13.06% >2360 μm and 2.29% >3350 μm), while still having 4.09% fine particles in the pan compared to the 1000 μm (8.35% >2360 μm ; 0.99% >3350 μm ; 3.18% in pan) sorghum.

Flowability is the ability of granular solids and powders to flow during discharge from transportation or storage containments. Poor flowability may result in several types of flow problems within the feed mill that can occur in the bin or silo including bridging, or the formation of an arch that prevents ingredients from flowing out. When producing pelleted complete diets, flowability issues may occur during the storage and handling of ground ingredients; however, the pelleting process largely mitigates flowability concerns in the finished complete diet. The flowability characteristics analyzed included: AoR, compressibility, COD, and CFI (Table 3).

In feed manufacturing, AoR is the most common measurement used to evaluate flowability. Ground ingredients with a low angle of repose represent those that flow more easily, while those with a high AoR represent those that are more cohesive and prone to bridging or clogging. This measurement is important for ingredient storage in bins, as it helps predict how a feed ingredient will behave during bin filling and discharge. Knowing the AoR ensures proper hopper slope when choosing bins, prevents feed buildup when considered, and maintains consistent feed delivery to mixers or feeders when concepts are applied correctly. The ground grains for this study numerically observed the best AoR at S1200 ($\sim 40^\circ$) and worst at S400 ($\sim 49^\circ$) with all other treatments intermediate (S600, S800, C800, S1000; $\sim 45^\circ$), as expected as

the d_{gw} increases, AoR decreases. These data agree with previous studies that analyzed AoR of increasing d_{gw} of corn (Jadhav et al. 2017) and sorghum (Friesen et al. 2024). With the resulting AoR values, S400 would be considered poor flowing material (46.0-55.9°). For C800, S600, S800, S1000, the AoR value decreased to a point that would characterize the ground sorghum as a passable flowing material (41.0-45.9°). The S1200 resulted in the lowest AoR and is characterized as being fair flowing material (36.0-40.9°).

Compressibility measures the change in volume of the sample when increasing levels of compressive force are applied and is influenced by factors including particle size distribution, particle shape, and particle texture (Freeman Technology, 2015). The compressibility of the S1200 treatment was classified as having a fair flow characteristic (16-20%), while the remaining ground grains were characterized as having a passable flow characteristic (21-25%). As sorghum d_{gw} increased, compressibility decreased which is in agreement with previous research that observed increasing d_{gw} leading to decreased compressibility (Braun et al. 2021).

The critical orifice diameter is determined using a powder flow ability test instrument (Flodex Model WG-0110, Paul N. Gardner Company, Inc., Pompano Beach, FL). The resulting COD is the size of the smallest orifice in a base plate disc through which the material in a cylinder will discharge. The smallest disk for the C800 and S400 grains would flow through were a 25- and 27-mm diameter hole, respectively, while the remaining ground sorghum would flow through a 18-22 mm diameter hole. The CFI is calculated by combining the results for AoR, compressibility, and COD. The S1200 treatment was the only treatment that resulted in a CFI flow description as fair (60-75). All remaining treatments were classified as passable (45-60).

During pelleting, all diets were steam conditioned for an average conditioning retention time of 30 seconds and a conditioning temperature range of 82.4-84.1°C. Average conditioning

temperatures and hot pellet temperatures are reported in Table 4. Pellet durability was greatest in the starter diets and lowest in the finisher diets, with PDI decreasing from 70% in the starter phase to 42%, 29%, and 24% in the Grower I, Grower II, and Finisher phases, respectively, when averaged across all treatments. When averaged across feeding phases, PDI values were 45%, 43%, 40%, 38%, 40%, and 41% for C800, S400, S600, S800, S1000, and S1200, respectively. Overall, PDI declined as feeding phase advanced, and no consistent treatment-related trends were observed across phases.

Growth Performance

From d 4-12, there were no evidence of differences ($P > 0.05$) in BWG or FI for broilers fed the corn-based control diet compared to those fed either of the sorghum-based diets. Broilers fed S400 had poorer ($P < 0.05$) FCR compared to those fed C800. There was no evidence of differences ($P > 0.240$) in broiler BWG or FCR when fed sorghum-based diets with varying sorghum d_{gw} . Increasing sorghum d_{gw} resulted in a tendency for decreased (quadratic, $P = 0.085$) FI, with broilers fed S400 having the greatest intake, and broilers fed the remaining treatments having similar FI.

From d 4-28, there were no evidence of differences ($P > 0.05$) in BWG, FI or FCR for broilers fed the corn-based control diet compared to those fed either of the sorghum-based diets. In addition, there were no evidence of differences ($P > 0.229$) in BWG or FI when broilers were fed sorghum-based diets with varying sorghum d_{gw} . Broilers fed diets with increasing sorghum d_{gw} had poorer FCR (linear, $P = 0.044$).

From d4 – 39, BWG of broilers fed the sorghum-based diets was greater ($P < 0.05$) than those fed the corn diets except for those fed the S1000. Broilers fed S1200 had increased ($P < 0.05$) FI compared to those fed the corn diets and broilers fed S400 had a tendency for increased

($P < 0.10$) FI compared to those fed the corn-based diets. Broilers fed the S400, S600, S1200 diets had improved ($P < 0.05$) FCR and those fed S800 had a tendency for improved ($P < 0.10$) FCR compared to those fed the corn-based diet. Broilers fed the S400 and S1200 diets had increased (quadratic, $P = 0.013$) BWG and FI compared to remaining sorghum diets. Broilers fed diets with increasing sorghum d_{gw} had poorer (linear, $P = 0.029$) FCR.

From d 4-49, overall BWG and FI were greater ($P < 0.05$) in broilers fed sorghum-based diets compared to those fed the corn-based diets. There was no evidence of differences ($P > 0.05$) in FCR between broilers fed the sorghum and corn-based diets. Increasing sorghum particle size tended to increase (linear, $P = 0.059$) FI and BWG (quadratic, $P = 0.056$) of broilers, with the majority of the improvements in BWG occurring when sorghum d_{gw} was increased from 1000 to 1200 μm . There was no evidence of differences ($P = 0.144$) in FCR of broilers fed diets with varying sorghum d_{gw} .

Traditional research evaluating tannin-containing sorghum as a replacement for corn in broiler diets has demonstrated reductions in growth performance due to its high tannin content (Gualtieri and Rapaccini, 1990). However, commercially available grain sorghum in the United States is considered tannin-free (U.S. Grains Council, 2025). Previous research using low-tannin or tannin-free sorghum has reported no differences in feed intake, weight gain, or feed efficiency when replacing corn with sorghum in broiler diets (Garcia et al., 2013; Tandiang et al., 2014; Ciurescu et al., 2023). In the present experiment, broilers fed U.S. sorghum-based diets exhibited increased BWG and FI compared with those fed corn-based diets, with similar or improved FCR.

Similarly, Saleh et al. (2019) reported that replacing corn with low-tannin sorghum in broiler diets from 15 to 27 d of age increased BWG and FI, resulting in improved FCR.

Based on the data collected in this experiment, sorghum can completely replace corn in broiler diets without negatively affecting growth performance through market age when sorghum is competitively priced compared to corn. In addition to considerations for least cost formulation and broiler growth performance, it is important to consider the influence sorghum has on feed manufacturing cost. Previous research has demonstrated that grinding corn requires more energy and results in lower production rates compared with sorghum (Martin, 1984; Healy et al., 1994). Collectively, these findings indicate that sorghum provides a dual advantage of maintaining broiler performance while improving feed mill efficiency, ultimately reducing overall cost of production.

One of the initial concerns associated with feeding coarse particles to broilers is the potential for ingredient selection by birds and segregation of ingredients during handling due to differences in particle size. However, pelleting mitigates these concerns by binding ingredients into larger, uniform aggregates. From a feed manufacturing standpoint, grinding cereal grains to a larger particle size is advantageous due to the substantial reduction in energy requirements and the increased throughput of the hammer mill. Previous research demonstrated that increasing hammer mill screen hole diameter from 2.3 mm to 6.3 mm reduced energy consumption by 35% when grinding corn (Braun et al., 2021). Similarly, Healy et al. (1994) observed a decrease in energy required to grind cereal grains and an increase in hammer mill production rate when increasing corn or sorghum particle size from 300 to 900 μm . Consequently, improvements in energy efficiency and production rate can reduce diet manufacturing costs when formulating sorghum-based diets and targeting coarser particle sizes.

A majority of the research evaluating the effects of cereal grain particle size on broiler performance has been conducted using corn. The effects of corn particle size on broiler performance have been inconsistent and appear to depend on several factors, including feed form and particle size distribution. Previous research has demonstrated that corn particle size influences broiler growth performance when mash diets are fed; however, growth performance is generally similar across corn particle sizes when diets are pelleted (Naderinejad et al., 2016; Rueda et al., 2024). Additionally, research has demonstrated that including a proportion of coarsely ground corn in diets prior to pelleting does not negatively affect or even improves broiler BW or FCR (Dozier et al., 2006; Xu et al., 2015a; Xu et al., 2015b). However, recent research demonstrated that starter broilers (d 0–21) fed pelleted diets containing corn ground to 2,036 μm had poorer FCR than those fed diets containing corn ground to 832 or 1,432 μm (Downs et al., 2023).

Previous research has determined that sorghum ground to a target particle size range of 450 to 850 μm results in similar growth performance in broilers (Rodgers et al., 2012; Silva et al., 2018). Selle et al. (2017) reported that increasing sorghum dgw from 780 to 1,400 μm in broiler diets fed from 7 to 28 d of age resulted in numerically improved weight gain and FCR. Collectively, these studies suggest that broilers tolerate a relatively wide range of sorghum particle sizes with minimal impact on overall performance, with potential improvements observed at coarser particle sizes. The present experiment extends these findings by demonstrating that larger particle sizes ($\geq 1,000$ μm) may increase FI and BWG without affecting FCR in broilers fed to 49 d of age. However, at 39 d of age, broilers fed both fine (400 μm) and coarse (1,200 μm) sorghum exhibited improved BWG, FI, and FCR compared with those fed intermediate particle sizes. Although this response contrasts with most previous particle size

research, Reece et al. (1986) reported similar findings, where broilers fed corn ground to 679 or 1,289 μm had improved BW gain and FCR compared with those fed diets containing corn ground to 987 μm .

Gizzard relative weight and pH

Broilers fed S400 had lower absolute and RGW compared with C800 ($P < 0.05$), whereas S1000 increased ($P < 0.05$) gizzard weight relative to corn. Within sorghum diets, increasing d_{gw} up to 1000 μm resulted in an increase in gizzard weight and RGW (quadratic, $P < 0.01$), indicating enhanced mechanical stimulation with coarser particles. These findings align with previous reports demonstrating that increased dietary particle size stimulates gizzard development measured by organ weight and RGW (Zaefarian et al., 2016). However, there was no further increase in gizzard development as the sorghum particle size increased past 1000 μm . Although this is contrary to the authors initial hypothesis, previous research has also demonstrated no further increase in gizzard weight when sorghum particle size exceeded 1055 μm (Selle et al., 2016).

Gizzard pH was greater in broilers fed S400 compared with corn-based diets ($P < 0.05$) and increasing sorghum d_{gw} tended to decrease gizzard pH (quadratic, $P = 0.06$). This response is consistent with the concept that coarse particles promote increased gizzard muscular activity and gastric acid secretion, resulting in lower luminal pH (Xu et al. 2015b; Naderinejad et al. 2016). Similarly, Jacobs et al., (2010) reported reduced gizzard pH and increased relative gizzard weight with coarser corn particle sizes. However, Selle et al. (2016) observed increases in gizzard weight with increasing sorghum particle size but did not detect differences in pH, suggesting that pH responses may depend on grain characteristics.

CONCLUSIONS AND APPLICATIONS

1. U.S. Sorghum can completely replace corn in broiler diets without negatively affecting growth performance through market age. In this experiment, broilers fed U.S. sorghum-based diets exhibited increased BWG and FI compared with those fed corn-based diets, with similar or improved FCR.
2. Grinding U.S. sorghum to coarser particle sizes ($\geq 1,000 \mu\text{m}$) improved gizzard development while maintaining growth performance. Targeting coarser particle sizes may reduce grinding energy use, increase hammermill throughput, and decrease equipment wear, ultimately lowering feed manufacturing cost per ton.
3. When economically competitive, U.S. sorghum provides an opportunity to reduce diet cost while maintaining broiler performance and enhancing gastrointestinal development. Additionally, the use of coarser U.S. sorghum particle sizes can improve feed mill efficiency, supporting both nutritional and manufacturing advantages.

ACKNOWLEDGEMENTS

The authors would like to express appreciation to the U.S. Sorghum Checkoff for funding the research projects here within. The authors would like to express appreciation to the Kansas State University Poultry Research Farm for use of their facilities.

DISCLOSURE

The authors disclose no conflict of interest.

REFERENCES

- Braun, M., K. Dunmire, C. Evans, C. Stark, J. Woodworth, and C. Paulk. 2021. Effects of Grinding Corn with Different Moisture Content on Subsequent Particle Size and Flowability. *Processes* 2021, Vol. 9, Page 1372-9. doi:10.3390/pr9081372
- Ciurescu, G. A. Vasilachi, L. Idriceanu, and M. Dumitru. 2023. Effects of corn replacement by sorghum in broiler chickens diets on performance, blood chemistry, and meat quality. *Ital. J. Anim. Sci.* 22:537-547. doi:10.1080/1828051X.2023.2212695
- Dozier III, W. A., K. Behnke, M. T. Kidd, and S. L. Branton. 2006. Effects of the addition of roller mill ground corn to pelleted feed on pelleting parameters, broiler performance, and intestinal strength. *J. Appl. Poult. Res.* 15:236-244. doi:10.1093/japr/15.2.236
- Downs, K. M., J. P. Gulizia, G. R. Harder, E. K. Stafford, S. J. Sasia, and W. J. Pacheco. 2022. Corn particle size variation effects on broiler performance, organ weights, and nutrient digestibility during the early growout period (day 1 to 21). *J. Appl. Poul. Res.* 32:100327. doi:10.1016/j.japr.2022.100327
- Fernandes, E. A., W. J. S. Pereira, L. Hackenhaar, R. M. Rodrigues, and R. Terra. 2013. The use of whole grain sorghum in broiler feeds. *Rev Bras Cienc Avic* 15. doi:10.1590/S1516-635X2013000300008
- Friesen, W. G., H. K. Ottot, C. R. Stark, and C. B. Paulk. 2024. Effect of Grinding and Pelleting Sorghum Grain Varieties with a Hammermill on Subsequent Particle Size, Flowability, and Pelleting Durability Index. *Swine Day proceedings in Kansas Agricultural Experiment Station Research Reports.*

Garcia, R. G., A. A. Mendes, I. C. L. Almeida Paz, C. M. Komiyama, F. R. Caldara, I. A. Naas, and W. S. Mariano. 2013. Implications of the use of sorghum in broiler production. *Braz. J. Poul. Sci.* 15:169-286.

Ghasemi-Aghgonbad, A., M. Olyayee, H. Janmohammadi, M. R. Abdollahi, and R. Kianfa. 2024. The Interactive Impacts of Corn Particle Size and Conditioning Temperature on Performance, Carcass Traits, and Intestinal Morphology of Broiler Chickens. *Animals* 2024, Vol. 14, Page 818 14. doi:10.3390/ani14050818

Gualtieri, M. and S. Rapaccini. 1990. Sorghum grain in poultry feeding. *World's Poul. Sci. J.* 46:246-254. doi.org/10.1079/WPS19900024

Healy, B. J., J. D. Hancock, P. J. Bramel-Cox, K. C. Behnke, and G. A. Kennedy, 1991.

Optimum particle size of corn and hard and soft sorghum grain for nursery pig and broiler chicks. *Swine Day proceedings in Kansas Agricultural Experiment Station Research Reports*

Healy, B. J., J. D. Hancock, G. A. Kennedy, P. J. Bramel-Cox, K. C. Behnke, and R. H. Hines.

1994. Optimum particle size of corn and hard and soft sorghum for nursery pigs. *J. Anim. Sci.* 72:2227-2236. DOI: 10.2527/1994.7292227x

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

Jadhav, H. T., C. Ozoh, S. T. MARRIPUDI, X. Cao, and K. A. Rosentrater. 2017. Studies on Ground Corn Flowability as Affected by Particle Size and Moisture Content. Spokane, Washington July 16 - July 19, 2017. doi:10.13031/aim.201701175

Kalivoda, J. R., C. K. Jones, and C. R. Stark. 2017. Impact of varying analytical methodologies on grain particle size determination. *J Anim Sci* 95. doi:10.2527/jas.2016.0966

- Moritz, A. H., W. C. Bridges, S. Wilson, M. E. Blair, R. E. Buresh, J. R. Strickland, and M. Arguelles-Ramos. 2022. Effects of select tannin-free grain sorghum varieties on the performance, carcass traits, intestinal morphology, and gene expression of jejunal mucosa of broiler chickens. *Prof Anim Sci* 38. doi:10.15232/aas.2022-02329
- Naderinejad, S., F. Zaefarian, M. R. Abdollahi, A. Hassanabadi, H. Kermanshahi, and V. Ravindran. 2016. Influence of feed form and particle size on performance, nutrient utilisation, and gastrointestinal tract development and morphometry in broiler starters fed maize-based diets. *Anim Feed Sci Technol* 215. doi:10.1016/j.anifeedsci.2016.02.012
- Pfost, H. B. 1976. *Feed Manufacturing Technology*. American Feed Manufacturing Association, Feed Production Council.
- Reece, F. N., B. D. Lott, and J. W. Deaton, 1986. Effect of environmental temperature and corn particle size on response of broilers to pelleted feed. *Poultry Sci.* 65:636-641. doi:10.3382/ps.0650636
- Rodgers, N. J., M. Choct, H. Hetland, F. Sundby, and B. Svihus. 2012. Extent and method of grinding of sorghum prior to inclusion in complete pelleted broiler chicken diets affects broiler gut development and performance. *Anim Feed Sci Technol* 171. doi:10.1016/j.anifeedsci.2011.09.020
- Rueda, M. S., S. Bonilla, C. d. Souza, J. D. Starkey, C. W. Starkey, L. Mejia, and W. J. Pacheco. 2024. Evaluation of particle size and feed form on performance, carcass characteristics, nutrient digestibility, and gastrointestinal tract development of broilers at 39 d of age. *Poult Sci* 103. doi:10.1016/j.psj.2024.103437
- Saleh, A. A., A. M. Abudabos, M. H. Ali, and T. A. Ebeid. 2019. The effects of replacing corn with low-tannin sorghum in broiler's diet on growth performance, nutrient digestibilities, lipid

- peroxidation and gene expressions related to growth and antioxidative properties. *J. Appl. Anim. Res.* 47:532-539. doi:10.1080/09712119.2019.1680377
- Selle, P. H., D. J. Cadogan, X. Li, and W. L. Bryden. 2010. Implications of sorghum in broiler chicken nutrition. *Anim Feed Sci Technol* 156. doi:10.1016/j.anifeedsci.2010.01.004
- Selle, P. H., H. H. Truong, A. Khoddami, A. F. Moss, T. H. Roberts, and S. Y. Liu. 2016. The impacts of hammer-mill screen size and grain particle size on the performance of broiler chickens offered diets based on two red sorghum varieties. *Br Poult Sci* 60. doi:10.1080/00071668.2016.1257777
- Silva, P. G., L. M. S. Oliveira, N. R. Oliveira, F. A. M. Júnior, M. R. S. Silva, D. A. Cordeiro, C. S. Minafra, and F. R. Santos. 2017. Effects of processing, particle size and moisturizing of sorghum-based feeds on pellet quality and broiler production. *Asian-Australas J Anim Sci* 31. doi:10.5713/ajas.17.0473
- Svihus, B. 2011. The gizzard: function, influence of diet structure and effects on nutrient availability. *Worlds Poult Sci J* 67. doi:10.1017/S0043933911000249
- Tandiang, D., M. Diop, A. Dieng, G. Yoda, N. Cisse, M. Nassium. 2014. Effect of corn substitution by sorghum grain with low tannin content on broilers production: Animal performance, nutrient digestibility and carcass characteristics. *J. Poul. Sci.* 13:568-574. doi:10.3923/ijps.2014.568.574.
- U.S. Grains Council, 2025. 2024-2025 Sorghum Quality Report.
- Xu, Y., C. R. Stark, P. R. Ferket, C. M. Williams, and J. Brake. 2015a. Effects of feed form and dietary coarse ground corn on broiler live performance, body weight uniformity, relative gizzard weight, excreta nitrogen, and particle size preference behaviors. *Poul. Sci.* 94:1549-1556. doi: 10.3382/ps/pev074.

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

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

Table 1. Analyzed composition of cereal grains (as-is basis)

Item	Corn	Sorghum
Mycotoxins		
Aflatoxin, ppb	< 2.0	< 2.0
Deoxynivalenol, ppm	0.11	< 0.10
Fumonisin, ppm	0.91	< 0.10
Proximate, %		
Moisture	10.25	12.25
Crude protein	7.79	9.35
Crude Fat	4.38	3.08
Crude Fiber	1.90	1.63
Ash	1.19	1.30
Indispensable AA, %		
Arginine	0.35	0.36
Histidine	0.23	0.25
Isoleucine	0.29	0.39
Leucine	0.92	1.26
Lysine	0.26	0.27
Methionine	0.18	0.17
Phenylalanine	0.38	0.50
Threonine	0.28	0.30
Tryptophan	0.05	0.06
Valine	0.37	0.49
Dispensable AA, %		
Alanine	0.58	0.87
Aspartic acid	0.54	0.64
Cysteine	0.18	0.18
Glutamic acid	1.46	2.04
Glycine	0.18	0.31
Serine	0.36	0.39
Tyrosine	0.22	0.29
Total AA	7.73	9.74

¹ Grain samples were collected upon receiving and sent to be analyzed for mycotoxins (aflatoxin, deoxynivalenol, and fumonisin) at ATC Scientific and proximate and amino acid analysis at the Agricultural Experiment Station Laboratories, at the University of Missouri-Columbia.

Table 2. Hammer mill settings and subsequent geometric mean diameter (d_{gw}) and geometric standard deviation (S_{gw}) when grinding corn and sorghum¹

Cereal Grain	Target	d_{gw} (μm)	S_{gw} (μm)	Screen size		Tip Speed (ft/min)
				Up (mm)	Down (mm)	
Sorghum	400	414	2.89	4.4	4.4	16,400
Sorghum	600	606	2.60	6.8	5.2	13,325
Sorghum	800	821	2.69	6.8	5.2	9,225
Sorghum	1000	1046	2.46	6.8	4.4	8,610
Sorghum	1200	1124	2.66	6.8	4.4	7,175
Corn	800	850	2.89	9.5	9.5	10,250

¹ Target grain particle sizes were achieved using a 25-horsepower hammermill (Model 22115, Bliss Industries LLC.) equipped with a variable frequency drive for a 100% tip speed of 20,500 ft/min.

Table 3. Analyzed physical analysis of ground cereal grains

Item, %	Corn			Sorghum		
	800	400	600	800	1000	1200
Particle size ¹						
d _{gw}	850	414	606	821	1046	1124
S _{gw}	2.89	2.89	2.60	2.69	2.46	2.66
Retained on screen, %						
3350 µm	3.15	0.00	0.00	0.30	0.99	2.29
2360 µm	8.47	0.20	0.90	3.18	7.36	10.77
1700 µm	14.58	1.76	5.51	11.92	17.79	21.14
1180 µm	20.10	11.17	18.94	32.08	34.39	34.50
850 µm	15.76	18.02	21.24	20.26	16.80	12.66
600 µm	11.23	16.55	16.03	9.53	7.26	4.49
425 µm	7.39	11.85	10.62	5.06	3.78	2.29
300 µm	4.93	8.72	7.21	3.28	2.29	1.69
212 µm	3.55	6.46	5.11	2.88	1.89	1.60
150 µm	2.36	4.80	3.51	2.28	1.39	1.40
106 µm	1.77	5.88	3.61	2.38	1.59	1.50
75 µm	1.08	4.51	2.40	1.69	0.99	1.10
53 µm	0.59	2.15	0.70	0.60	0.30	0.50
Pan	5.02	7.93	4.21	4.57	3.18	4.09
Flow ability metrics ²						
Angle of Repose,	45.9	48.9	45.7	45.0	44.8	40.5
Compressibility, %	24.7	23.8	23.5	24.1	23.0	20.9
Critical Orifice Diameter, mm	25	27	20	20	22	18
Composite Flow Index	49.6	46.0	56.1	56.1	54.8	63.5
Density, g/mL						
Bulk Density	0.66	0.66	0.68	0.69	0.66	0.72
Tapped Density	0.81	0.87	0.88	0.91	0.86	0.91

¹Particle size was determined using a Tyler Ro-Tap and U.S. standard 13-sieve stack for 10 minutes with flow agent. d_{gw}; geometric mean diameter, S_{gw}; geometric standard deviation.

²Flowability characteristics were measured utilizing methodology outlined by Kalivoda et al., (2017).

Table 4. Diet formulation for basal diets across phases.¹

Ingredient	Starter		Grower 1		Grower 2		Finisher	
	Corn, %	Sorghum, %	Corn, %	Sorghum, %	Corn, %	Sorghum, %	Corn, %	Sorghum, %
Grain ²	59.46	59.28	64.98	64.77	69.06	68.81	72.30	72.04
Soybean meal, 46%	34.09	34.28	29.59	29.81	26.24	26.48	23.26	23.51
Limestone	0.90	0.83	1.04	0.96	0.98	0.90	0.97	0.89
Dicalcium phosphate	1.97	2.06	1.02	1.12	0.88	0.98	0.84	0.95
Sodium Chloride	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
L-Lysine HCl	0.17	0.18	0.16	0.17	0.13	0.14	0.12	0.13
DL-Methionine	0.33	0.31	0.29	0.27	0.25	0.24	0.22	0.20
L-Threonine	0.12	0.12	0.08	0.08	0.05	0.05	0.03	0.02
L-Valine	0.04	-	0.02	-	-	-	-	-
Vitamin Trace	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Mineral Premix ³	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Phytase ⁴	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Choline chloride	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.06
Titanium dioxide	0.50	0.50	0.50	0.50	-	-	-	-
Soy oil	1.71	1.71	1.61	1.61	1.69	1.69	1.54	1.54
Total	100	100	100	100	100	100	100	100

¹ Diets were formulated to meet or exceed the nutrient recommendations set forth by Cobb Vantress (2022). Phases were Starter d 4-12, Grower 1 d 12-28, Grower 2 d 28-39, Finisher d 39-49.

² Grain was either yellow dent corn or mixed red sorghum locally sourced in Manhattan, KS

³ NB3000 (NutraBlend, Nevada, MO)

⁴ Quantum Blue 10G (AB Vista, Plantation, FL) 10,000 FTU/g

Table 5. Pelleting temperatures and pellet quality of pelleted diets^{1,2}

Item, %	Corn		Sorghum			
	800	400	600	800	1000	1200
Conditioning Temp., °F						
Starter	181.1	182.8	181.8	180.5	181.4	181.0
Grower I	183.4	180.8	180.9	180.4	181.5	182.5
Grower II	180.7	181.3	181.3	180.9	181.4	181.6
Finisher	181.4	180.8	180.7	181.8	180.5	181.2
Hot Pellet Temp., °F						
Starter	193.5	196.3	193.6	192.9	194.6	193.2
Grower I	188.2	190.9	191.0	189.2	191.6	189.4
Grower II	189.4	192.3	191.6	192.6	193.8	194.2
Finisher	190.6	196.1	194.9	195.4	197.6	196.7
Pellet Durability Index, % ³						
Starter	68	70	73	70	69	67
Grower I	55	38	46	40	39	31
Grower II	29	42	25	27	21	29
Finisher	27	22	15	15	31	36

¹Treatments were pelleted using a 1-ton 30-horsepower pellet mill (1012-2 Master Model, California Pellet Mill) equipped with an 11/64 in × 1 3/8 in (length: diameter 8) pellet die.

²The values for conditioning and hot pellet temperatures are the averages of 3 measurements taken at evenly spaced intervals over the duration of the pellet run

³Holmen NHP100 for 60s; Samples were analyzed in triplicate

Tabel 6. Growth performance of broilers fed diets with a corn base or variable particle sizes of sorghum

Item	C800	S400	S600	S800	S1000	S1200	SEM	Lin ²	Quad ²
BWG, g									
d 4-12	269	282	276	282	272	279	4.3	0.448	0.480
d 4-28	1559	1685	1596	1656	1572	1636	39.2	0.289	0.229
d 4-39	2743	3124*	2984*	3020*	2928	3153*	69.7	0.991	0.013
d 4-49	3693	4067*	4201*	4010*	4065*	4376*	90.9	0.076	0.056
FI, g									
d 4-12	318	343	328	332	330	338	6.3	0.685	0.085
d 4-28	2129	2241	2195	2218	2172	2211	43.4	0.494	0.469
d 4-39	4171	4444 [†]	4312	4375	4347	4545*	90.5	0.328	0.049
d 4-49	5871	6474*	6600*	6430*	6552*	6880*	138.9	0.059	0.131
FCR, g/g									
d 4-12	1.18	1.23*	1.20	1.21	1.21	1.21	0.011	0.582	0.240
d 4-28	1.37	1.33	1.35	1.36	1.38	1.35	0.014	0.044	0.051
d 4-39	1.49	1.42*	1.43*	1.45 [†]	1.49	1.44*	0.013	0.029	0.059
d 4-49	1.58	1.59	1.57	1.60	1.61	1.57	0.014	0.760	0.144

¹ 864 COBB by product breeders were allotted to 72 pens (n=10/pen) at 4 days of age, to begin dietary treatments of C (corn) or S (sorghum) based diets at variable μ m, 400, 600, 800, 1000 or 1200. Body weight gain (BWG), feed intake (FI) data were collected for day 4-12, 13-28, 29-39, and 40-49 with feed conversion ratio (FCR) being calculated for each phase and adjusted.

² Data were analyzed using PROC GLIMMIX of SAS 9.4 with linear and quadratic contrasts

* Denotes statistical difference ($P \leq 0.05$) between sorghum treatments compared back to the C800 (control) treatment utilizing Dunnet's test.

[†] Denotes statistical tendency ($0.05 \leq P \leq 0.10$) between sorghum treatments compared back to the C800 (control) treatment utilizing Dunnet's test.

Table 7. Gizzard weight relative to body weight and pH in broiler chickens¹

Parameter	C800	S400	S600	S800	S1000	S1200	SEM	Lin ²	Quad ²
BW, g	4161.4	4352.3	4253.1	4291.8	4482.6 [†]	4310.9	105.2	0.63	0.98
Gizzard, g	43.6	37.7*	41.1	44.3	47.7*	43.7	1.41	< 0.01	< 0.01
Relative	1.05	0.87*	0.97 [†]	1.04	1.07	1.02	0.03	< 0.01	< 0.01
Gizzard pH	3.07	3.61*	3.29	3.24	3.11	3.29	0.14	0.05	0.06

¹ 864 COBB by product breeders were allotted to 72 pens (n=10/pen) at 4 days of age, to begin dietary treatments of C (corn) or S (sorghum) based diets at variable microns, 400, 600, 800, 1000 or 1200. On day 49, 2 average birds per pen were sacrificed for the collection of gizzard pH and weight. Gizzard pH was measured using a portable pH and temperature meter (HI99165, Hanna Instruments, Woonsocket, RI). Relative gizzard weight was collected after contents were probed for pH and the organ was rinsed with distilled water. Data are reported as a ratio of gizzard weight to body weight.

² Data were analyzed using PROC GLIMMIX of SAS 9.4 with linear and quadratic contrasts

³ Dunnet's test was utilized for comparison of S treatments back to C (control) treatment.

* Denotes statistical difference ($P \leq 0.05$) between sorghum treatments compared back to the C800 (control) treatment utilizing Dunnet's test.

[†] Denotes statistical tendency ($0.05 \leq P \leq 0.10$) between sorghum treatments compared back to the C800 (control) treatment utilizing Dunnet's test.