Dietary roller–milled sorghum improves broiler efficiency and whole sorghum improves gut development

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Summary

The effects of particle size and type of milling of dietary sorghum for broilers were examined. Sorghum treatments were: whole (WS), hammer–milled with a 3 mm screen (HM3), roller–milled with 0.15 mm roller spacing (RM0.15) and hammer–milled with a 1 mm screen (HM1). Diets HM3 and RM0.15 were milled to the same particle size. All diets were pelleted. Birds fed RM0.15 were more efficient than those fed the other treatments at 21 and 35 days of age (d), but there was no effect on cumulative feed intake and bodyweight at 35 d. At 35 d, there was no particle size effect of hammer–milled sorghum on performance; birds fed WS were least efficient. Nitrogen–corrected apparent metabolisable energy (AME_n) was increased by whole sorghum relative to that of processed sorghum. Relative gizzard weight was proportional to pre–pellet particle size at 21 d and was decreased by HM1 relative to the other treatments at 35 d. Relative proventriculus weight was increased by HM1 at 21 d and 35 d. Neither particle size nor processing type affected relative weights of intestinal segments. Digesta pH decreased in the gizzard and increased in the duodenum for WS relative to HM1. At 21 d, the surface area of duodenal digesta particles was smaller for WS and HM1 than for HM3 and RM0.15. At 35 d, the specific surface area of duodenal digesta particles was highest for WS. Feed conversion and gut development were improved by roller–milled sorghum. Whole sorghum improved gut development and AME_n at the expense of performance.

Keywords: broiler, particle size, feed conversion, digesta pH, gizzard, roller–mill, hammer–mill, whole grain, sorghum

Introduction

The function of the upper digestive tract of the domestic chicken is to degrade feed to a form that is amenable to digestion in the intestine. Because birds have no teeth, the organs of the upper digestive tract are responsible for mechanical breakdown of ingested feed. Stimulation of the development and function of the upper digestive tract by coarse feed is essential for the production of digesta with physical and chemical characteristics favourable for enzymatic degradation (Hetland and Svihus 2003; Svihus *et al*. 2004).

Work reported by Dibner (1997) shows that development of the digestive tract post–hatch, influenced by ingredient texture, is important to broiler health. Cumming (1992) found that ingestion of coarse feed particles stimulated gizzard development, reduced coccidiosis and contributed to greater hydrochloric acid production in the proventriculus. In modern feed milling systems, grains undergo some form of processing to decrease grain particle size, improve uniformity of ingredient distribution, improve pellet quality, disrupt seed coatings and starch granules or matrices of proteins binding starch, and to increase the surface area of the grain to improve endogenous enzymatic degradation. However, these processing methods are not necessarily aimed at optimising the digestive processes of the broiler. A number of studies have examined the effects of feed particle size on performance, organ development and digestive processes of broiler chicks and layers (Douglas *et al*. 1990; Lott *et al*. 1992; Nir *et al*. 1995; Nir *et al*. 1994a; Nir *et al*. 1990; Nir *et al*. 1994b; Reece *et al*. 1985; Reece *et al*. 1986a; Reece *et al*. 1986b). Several authors have emphasised the use of whole grains, coarse feed and fibre particles in broiler feed and their associated benefits on nutrient digestion, utilisation (Rogel *et al*. 1987; Svihus and Hetland 2001; Svihus *et al*. 2004) and performance (Lott *et al*. 1992; Nir *et al*. 1990; Reece *et al*. 1985; Reece *et al*. 1986a; Reece *et al*. 1986b). Several European countries are currently incorporating whole grains into pelleted broiler rations to improve efficiency. Other benefits associated with texture and particle size include improved calcium solubilisation (Guinotte *et al*. 1995) and increased calcium and phytate phosphorus retention in broiler chicks (Kilburn and Edwards 2001).

Feed particles only advance through to the intestine of the broiler when they are small enough to leave the gizzard (Clemens *et al*. 1975; Hetland *et al*.

2002). Larger particles will be retained longer in the upper tract, facilitating a greater extent of digestion. Most studies on whole grains have involved mash (Davis *et al*. 1951; Douglas *et al*. 1990) or pelleted diets with a whole–grain supplement (Salah Uddin *et al*. 1996; Svihus *et al*. 2004). In such studies, birds are able to select particles from the feed as shown by Portella (1988), Rose *et al*. (1986) and Davis *et al*. (1951). Olver and Yonker (1997), and Munt *et al*. (1995) showed that broilers that are able to choice–feed perform poorly relative to birds with access to diets for which choice feeding is restricted or absent (pelleted diets). This sub–optimal performance is believed to be due to selection of feed particles for size rather than nutritive value, resulting in inadequate intake of some dietary components and excess intake of other components.

Many studies that compared roller–milling with hammer–milling did not use equivalent particle sizes, as the products of various types of mill often have vastly different particle geometric mean diameters (Reece *et al*. 1985; Douglas *et al*. 1990). This allows for indirect comparison between milling methods and particle sizes because the effect of particle size is influenced by mill type and *vice versa*. It has been shown that the effects of milling method and pelleting are additive (Nir *et al*.1995). This is in contrast to the study conducted by Reece *et al*. (1985), in which mill–type effects were eliminated by pelleting. In the growing broiler, there is an energy and nutrient trade–off between growth of muscle, visceral tissues and maintenance. The goal of producers is to maximise muscle growth and minimise the energy and nutrient costs associated with non–profitable tissue growth and maintenance. The first hypothesis for this experiment was that a diet containing large particles would result in improved nutrient digestion and reduced feed conversion ratio (FCR). We thought that the method by which feed is ground may influence the way in which it is broken down and digested, irrespective of the size of the particle. The second hypothesis was that roller–milled sorghum would elicit a better digestive response than hammer–milled sorghum of equal mean particle size

Materials and methods

Treatments

A semi–purified diet consisting of 75% sorghum and 12% isolated soy protein (Table 1) was used. Prior to processing, the sorghum was sieved to remove excess debris and dust. Four sorghum diets, differing in mean particle size and processing method were used: whole (WS), hammer–milled with a 3 mm screen (HM3), roller–milled with 0.15 mm roller spacing (RM0.15) and hammer–milled with a 1 mm screen (HM1). RM0.15 was ground to a mean particle size equal to that of HM3. Diets WS and HM1 represented extreme variations from the intermediate particle sizes used in diets HM3 and RM0.15. HM3 was used as a control, as it was similar to processing methods used in feed milling.

After sieving, the sorghum was divided into four portions corresponding to the four treatments. After a 1 mm screen was fitted to a commercial hammermill (Münch–Edelstahl, Wuppertal, Germany, licensed by Bliss, USA), one portion of sorghum was fed through the machine to yield the sorghum used for treatment HM1. The hammermill was then fitted with a 3 mm screen, and a second portion of sorghum was fed through the mill to yield the sorghum component of HM3. A representative sample of HM3 was dry sieved using a Retsch AS 200 sieve (F. Kurt Retsch GmbH & Co., Haan, Germany) and the mean particle size was calculated. Particle size of dry feed and digesta was measured using a Mastersizer 2000 LASER diffraction particle size analyser and Sirocco 2000 and Hydro 2000G accessories (Malvern Instruments Ltd., UK) for dry and wet samples, respectively.

Two sets of rollers of a commercial roller–mill (Model DP 900–12, Roskamp, Indiana, USA) were adjusted to yield a mean particle size equal to that of HM3 sorghum. The spacings were 0.15 mm for the top rollers and 0.15 mm for the bottom rollers. The resulting milled sorghum was used in the third dietary treatment (RM0.15). All dietary components, except for soy oil, were added to the sorghum and mixed using a Dinnisen mixer (Pegasus Menger 400 1, Sevenum, Holland).

Table 1 Composition of the semi–purified diet.

Ingredient	Inclusion level (g/kg)
Sorghum[A]	750
Fishmeal 70%	40
Isolated Soy Protein 90%	120
Soybean oil	39.8
Monocalcium phosphate	2.00
Ground limestone	8.00
Sodium chloride	2.50
Vitamin premix[1]	3.00
Mineral premix[2]	1.50
Manganese oxide	0.10
Titanium dioxide	5.00
DL–Methionine	3.00
L–Lysine	3.00
L–Threonine	1.00
Choline chloride	1.10

[A]Sorghum differing in particle size and subjected to hammer– or roller–milling
[1]Vitamin premix supplied (per kg of diet): retinyl acetate, 5.15 mg; cholecalciferol, 0.10 mg; DL–tocopheryl acetate, 75 mg; menadione, 9 mg; pyridoxine, 6 mg; riboflavin, 24 mg; Ca–pantothenate, 26.3 mg; biotin, 0.39 mg; thiamine, 3.75 mg; niacin, 75 mg; cobalamin, 0.03 mg; folic acid, 3.75 mg
[2]Mineral premix supplied (per kg of diet): Fe, 75 mg; Mn, 60 mg; Zn, 105 mg; Cu, 15 mg; I, 0.75 mg; Se, 0.3 mg

All diets were steam–conditioned in a double conditioner (Münch–Edelstahl, Wuppertal, Germany) for 60 seconds at an average conditioning temperature of 75ºC, and soy oil was added at this stage. The diets were then steam–pelleted (Münch–Edelstahl, Wuppertal, Germany) using a 3 mm die (42 mm thick). The pellet press had two closed–end corrugated rolls set at approximately 0.25 mm relative to the inner surface of the pellet die. Pellet samples were taken immediately after the pellets exited the press and stored in a polystyrene box fitted with an electronic thermometer to measure post–pelleting temperature. All diets were cooled after pelleting in a Miltenz Counter Flow Cooler (Auckland, New Zealand). Mean post–pelleting temperatures, energy consumption and production rates of the pellet press for the four diets are presented in Table 2.

Bird husbandry

Three hundred day–old male broilers (Ross 308) were purchased from a commercial hatchery, divided into eight groups and each group was allocated a separate brooder cage. The birds were fed a commercial wheat–based starter crumble until 11 days of age, at which time birds were weighed to calculate the average weight for each group. A total of 192 birds were then weighed separately and selected for the experiment if their bodyweight was within 15% of the average weight of the brooder group. Ninety six cages (22 cm × 38 cm × 38 cm), suitable for housing modern broiler chicks from 10–12 days of age to five weeks of age, were used. Adjacent cages shared a common drinker line and were separated by wire mesh. The cage floors were constructed of wire mesh to allow excreta collection and were padded with rubber tubing. Birds received a total of 16 h of light per day with two four–hour dark periods during the night in the brooder phase and for the duration of the experiment. The ambient temperature of the experimental room was adjusted so that the temperature was 28ºC when the birds were 11 days old and decreased to 25ºC by 21d. From 21d, the temperature was maintained at 25ºC. Feed and water were provided *ad libitum*. During the period 11–21 d, each cage contained two birds. At 21 d, one bird per cage was slaughtered for dissection. At 35 d, the remaining birds were slaughtered for dissection. At 25 d, all birds were fasted for six hours, feed and birds were weighed, and excreta trays placed under birds for excreta collection. Excreta were collected for three consecutive days at the same time of day that the trays were first placed under the cages. Daily collections of excreta were pooled and frozen at –20ºC. The birds and feeds were weighed at the completion of excreta collection.

Measurements

Bodyweights were recorded at 11 days of age, 14 days of age and weekly thereafter. Feed refusals were weighed at the time of weighing, and additions to each feeder were made as needed. At 21 days of age, one bird per cage was euthanized using CO_2 gas. At 35 days of age, the dissection procedure was repeated. The proventriculus, gizzard, jejunum and ileum were weighed with and without digesta contents, and the duodenum was weighed without contents only. Gizzard and duodenum digesta pH was recorded. Digesta was collected from the duodenum and refrigerated immediately for particle size analysis.

All organs were cleaned of external fat and mesentery tissue before weighing. Excreta collected for AME_n determination were thawed prior to homogenisation. A sample of the wet digesta was then weighed. Wet samples were dried for 12 h at 104ºC, cooled to room temperature in a desiccator, weighed again, and the gross energy contents were determined using a Parr 1281 adiabatic calorimeter (Moline, Illinois, USA). Gross energy of the diets was also determined.

Statistical analyses

All statistical analyses were done using one–way analysis of variance (StatGraphics Plus version 5.1 — Professional Edition, Manugistics Inc., Rockville, Maryland, USA). Differences between means were determined using Duncan's multiple comparison tests, and differences were considered significant at a confidence interval of 95% ($P<0.05$).

Results

Table 3 shows that from 11–21 days of age, broiler bodyweight gain was increased by ~5% ($P<0.05$) by feeding a diet based on hammer–milled sorghum of intermediate particle size (HM3) compared to a diet based on a fine (HM1) or coarse particle size (WS). Over the same time period, feed intake was reduced ($P<0.001$) in birds fed diets containing fine, ground sorghum (HM1) or roller–milled sorghum (RM0.15). Broilers fed the diet containing unprocessed sorghum were least efficient ($P<0.0001$), followed by diets based on sorghum

Table 2 Production characteristics of the four sorghum diets.

Treatment	WS	HM3	RM0.15	HM1
Pellet temperature (ºC)	83.9	82.3	81.8	84.0
Power consumption (A)	18–20	15–16	15–16	15–17
Production rate (kg/hr)	750–800	800	800	800
Feeder rate (%)	40–45	45–50	45–50	45–50

processed with a hammer–mill; birds that were fed the roller–milled sorghum were the most efficient. Feed efficiency was improved (*P*<0.0001) by 3% by roller–milled sorghum relative to hammer–milled sorghum at equal pre–pellet particle sizes. Birds fed an intermediate particle size were heavier (*P*<0.05) at 35 d than those fed WS but not significantly more so than those fed HM1. Over the whole experimental period, there were no treatment effects on cumulative feed intake. However, the effect of sorghum processing type on FCR from 11–21 d persisted to the end of the experiment, and the most efficient treatment (*P*<0.0001) was roller–milled sorghum. Furthermore, the RM0.15 group had a FCR ~3% superior (*P*<0.0001) to that of the hammer–milled sorghum–fed treatments, and 7% better than that of the WS treatment.

Increasing the particle size of sorghum in the diets resulted in decreases in proventriculus weight and increases in the weight and holding capacity of the gizzard at 35 d (Table 4). At 21 d, birds fed a pelleted diet containing sorghum that was not finely hammer–milled had lighter proventriculi and heavier gizzards (*P*<0.0001). At the same age, birds had the heaviest gizzards (*P*<0.0001) when fed a diet containing unprocessed sorghum in pellets. Gizzard content weight was decreased with respect to all other treatments when fine sorghum was fed. Gizzard relative weight and content were significantly correlated at 21 d and 35 d (*P*<0.05). There was no significant effect of sorghum processing type prior to pelleting on small intestinal segment weight. At 35 days of age, proventriculus weight was increased (*P*<0.0001) and gizzard weight

Table 3 Mean bodyweight (BW) gain, feed intake and feed conversion ratio (FCR) of 21– and 35–day–old male broilers fed sorghum–based diets with four levels of pre–pelleting processing[1].

Treatment	WS	HM3	RM0.15	HM1	*P* value
21 d of age					
BW gain[2] (g)	614.3^{a}	643.9^{b}	638.2^{ab}	615.2^{a}	<0.05
Feed intake[3] (g)	868.7^{b}	875.7^{b}	837.5^{a}	823.8^{a}	<0.001
FCR[4] (g/g)	1.41^{c}	1.36^{b}	1.31^{a}	1.34^{b}	<0.0001
35 d of age					
BW gain[2] (g)	1823.3^{a}	1905.2^{b}	1916.4^{b}	1865.7^{ab}	<0.05
Feed intake[3] (g)	2853.8	2902.2	2795.9	2804.5	NS
FCR[4] (g/g)	1.57^{c}	1.52^{b}	1.46^{a}	1.50^{b}	<0.0001

[1]Row means with different superscripts differ significantly
[2]Bodyweight gain from 11 d of age
[3]Cumulative feed intake from 11 d of age
[4]21 d FCR calculated and averaged for the two birds from 11–21 d of age, 35d FCR calculated from 11–35 d of age and averaged for the two birds for the period, 11–21 d of age

Table 4 Mean relative organ weights (g/kg liveweight) of 21– and 35–day–old male broilers fed diets with four types of pre–pelleting processing[1].

Treatment	WS	HM3	RM0.15	HM1	*P* value
21 d of age[2]					
Proventriculus	4.59^{a}	4.25^{a}	4.53^{a}	5.08^{b}	<0.01
Gizzard	18.61^{c}	16.81^{b}	17.18^{b}	14.43^{a}	<0.0001
Gizzard content	10.17^{b}	9.24^{b}	10.49^{b}	4.37^{a}	<0.0001
Duodenum	6.54	6.95	6.46	6.86	NS
Jejunum	11.01	11.47	10.83	11.65	NS
Ileum	8.60	8.35	8.44	8.88	NS
35 d of age[2]					
Proventriculus	3.25^{a}	3.46^{a}	3.62^{a}	4.53^{b}	<0.0001
Gizzard	13.94^{b}	13.38^{b}	13.27^{b}	11.40^{a}	<0.001
Gizzard content	7.17^{c}	5.92^{bc}	5.47^{b}	1.86^{a}	<0.0001
Duodenum	4.24	4.10	4.16	4.40	NS
Jejunum	8.29	8.23	7.81	8.50	NS
Ileum	6.72	7.16	6.96	6.59	NS

[1]Row means with different superscripts are statistically different
[2]Values for relative organ weights represent weights of empty organs

decreased (*P*<0.001) by finely ground sorghum in pellets compared to all other treatment groups. Gizzard content was decreased (*P*<0.0001) by the HM1 diet compared to all other treatments. Birds fed the WS diet retained significantly more digesta in the gizzard than those fed the RM0.15 diet, but not more than birds fed the HM3 diet. Two deaths occurred during the trial: one bird allocated to the HM3 treatment (ascites) and one allocated to the WS treatment (cause of death unknown). One bird from the HM3 treatment was not used for sampling at 35 d of age because of ascites.

Gizzard and duodenum digesta pH values of 21– and 35–day–old and broilers were influenced by sorghum processing type prior to pelleting (Table 5). At 21 days of age, birds fed the finest ground diet (HM1) had a significantly higher (*P*<0.0001) gizzard pH than all those of other treatment groups. Conversely, duodenal pH tended to decrease with the HM1 diet compared to the WS diet (*P* = 0.0534), but neither of the intermediate particle size diets had a significantly increased pH relative to HM1. At 35 days of age, gizzard pH of WS birds was reduced (*P*<0.0001) relative to those of all other diets. Furthermore, the HM3 and RM0.15 diets reduced (*P*<0.0001) gizzard pH compared to the HM1 diet. Duodenum pH was increased (*P*<0.01) by WS compared to RM0.15 and HM1. Similarly, duodenum pH was decreased (*P*<0.01) by HM1 compared to WS and HM3.

Nitrogen–corrected AME was higher for the WS sorghum treatment than for the other dietary treatments (*P* = 0.0047) (Table 6). This was reflected in the GE/ AME_n ratio. The ratio of the gross to apparent metabolisable energy was calculated to eliminate the effect of differences between dietary GE contents.

Before the feeds were mixed, the volume–weighted means of HM3 and RM0.15 were not significantly different, but both treatments had greater (*P*<0.0001) volume–weighted means than HM1 (Table 7). The hammer–milled sorghum preparations had greater specific surface areas than roller–milled sorghum, and area was greatest (*P*<0.0001) for the most finely ground diet. Ground sorghum particle uniformity was greatest (*P*<0.0001) for the HM1 diet and least for the RM0.15 diet. When the diets were mixed, the volume–weighted mean of the three diets was again higher for HM3 and RM0.15 and lower for HM1, but the difference between HM3 and RM0.15 was significant (*P*<0.0001). Specific surface area was greatest (*P*<0.0001) when volume–weighted and surface–weighted means in mixed feed were lowest, and *vice versa*. When mixed, the uniformity of feed was markedly decreased for RM0.15 and HM3 compared to the ground sorghum preparations, but was not greatly different for the HM1 diet. The pattern of uniformity between diets was not different when the feed was mixed compared with the ground sorghum preparations; uniformity was lowest for RM0.15 and highest for HM1 (*P*<0.0001).

Duodenal digesta particle characteristics illustrated in Table 8 show that the volume–weighted mean was largest for the HM1 treatment. The specific surface area of the digesta particles was highest (*P*<0.0001) in birds fed the intermediate particle sizes for d 21 and in those fed the WS treatment for d 35.

Discussion

This study showed that the effects of roller–milling (vs. hammer–milling) on FCR are still apparent after pelleting. That is, roller–milling improved FCR compared with hammer–milling even when mean particle sizes were similar. Similar effects of feeding roller–milled barley were observed by Svihus *et al*. (1997).

Table 5 Mean pH of gizzard and duodenum digesta in 21– and 35–day–old male broilers fed sorghum–based diets with different types of pre–pelleting processing[1].

Treatment	WS	HM3	RM0.15	HM1	*P* value
21 d of age					
Gizzard	3.39^a	3.39^a	3.38^a	3.92^b	<0.0001
Duodenum	6.06^b	5.99^{ab}	6.04^{ab}	5.97^a	0.053
35 d of age					
Gizzard	3.14^a	3.48^b	3.48^b	4.16^c	<0.0001
Duodenum	5.90^c	5.87^{bc}	5.70^{ab}	5.57^a	<0.01

[1]Row means with different superscripts are statistically different

Table 6 Nitrogen–corrected apparent metabolisable energy (AME_n) and gross energy (GE) : AME_n ratios for four sorghum–based diets[1].

Treatment	WS	HM3	RM0.15	HM1	*P* value
AME_n[2] (MJ/kg DM)	13.85^b	13.47^a	13.51^a	13.60^a	0.0047
GE/AME_n[3] (MJ/kg)	0.807^b	0.791^a	0.786^a	0.783^a	0.0025

[1]Row means with different superscripts are statistically different
[2]AME_n calculated using excreta taken over three consecutive days
[3]GE/AME_n ratio accounts for differences in GE of the feed

Jones and Taylor (2001) found that whole triticale in pelleted diets improved FCR and gastrointestinal tract development, and reduced the incidence of ascites relative to pelleted milled grain. The use of a roller–mill to grind sorghum to a particle size equal to that of sorghum ground through a hammer–mill resulted in a better FCR when diets were pelleted, but whole sorghum increased FCR and not bodyweight. Reece *et al*. (1985) reported a reduction in FCR and heavier body weights at 21 d for roller–milled corn compared with hammer–milled corn although particle sizes differed (814 µm, hammer–mill; 1343 µm, roller–mill). Svihus *et al*. (1997) reported improved FCR and lower gizzard weights in birds fed rolled barley compared with birds fed whole barley. However, Douglas *et al*. (1990) found that rolled sorghum increased FCR and reduced weight gain compared with hammer–milled grain.

The use of unprocessed sorghum in the feed mix prior to pelleting enhances gizzard development, reduces pH in the gizzard and increases pH in the duodenum at 21 d. Many studies have shown that the use of coarse feed particles is associated with greater gizzard weights (Forbes and Covasa 1995; Munt *et al*. 1995; Svihus *et al*. 2004) and smaller proventriculus weights (Riddell 1976; Nir *et al*. 1995; Jones and Taylor 2001). Svihus *et al*. (2004) showed that increased bile and amylase activity in the jejunum, increased pancreas and gizzard size, and increased the concentration of bile salts in the gizzard are associated with whole wheat diets. This indicates that digestive processes and the production of digestive enzymes are increased by whole wheat, and that it stimulates the upper digestive tract. Higher bile content in the gizzard of birds fed whole wheat indicates that gizzard–proventriculus reflux may also have improved digestion by exposing digesta to gastric secretions more than once. Apparent metabolisable energy was greatest for the WS treatment, which differs from the findings of McIntosh *et al*. (1962) and Salah Uddin *et al*. (1996), but is in accordance with the findings of Preston *et al*. (2000), Svihus *et al*. (1997) and Svihus *et al*. (2004). A possible explanation for the higher AME_n of WS is that coarser feed texture stimulated more efficient digestion. This may be due to greater endogenous enzyme secretion, digesta flow from

Table 7 Mean particle characteristics of milled sorghum and mixed feed (pre–pelleting) of three sorghum–based diets[1].

Treatment	HM3	RM0.15	HM1	*P* value
Ground sorghum[2]				
Volume–weighted mean (µm)	743.7[b]	739.2[b]	446.8[a]	<0.0001
Uniformity	0.52[b]	0.49[a]	0.55[c]	<0.0001
Specific surface area (m^2/g)	0.029[b]	0.023[a]	0.036[c]	<0.0001
Surface–weighted mean (µm)	209.5[b]	260.4[c]	166.8[a]	<0.0001
Mixed feed[3]				
Volume–weighted mean (µm)	623.1[b]	668.2[c]	386.9[a]	<0.0001
Uniformity	0.67[b]	0.58[a]	0.75[c]	<0.0001
Specific surface area (m^2/g)	0.035[b]	0.031[a]	0.053[c]	<0.0001
Surface–weighted mean (µm)	170.2[b]	190.4[c]	114.0[a]	<0.0001

[1]Row means with different superscripts are statistically different
[2]Grain was sieved to remove excess debris prior to grinding
[3]Milled grain mixed with minor ingredients

Table 8 Mean particle characteristics of duodenal digesta for 21– and 35–day–old male broilers fed four sorghum–based diets[1].

Treatment	WS	HM3	RM0.15	HM1	*P* value
21 d of age					
Volume–weighted mean (µm)	20.57[b]	20.22[ab]	17.87[a]	24.81[b]	<0.03
Uniformity	1.97	1.95	1.80	2.32	NS
Specific surface area (m^2/g)	1.037[a]	1.079[b]	1.105[b]	1.009[a]	<0.0001
Surface–weighted mean (µm)	5.85[bc]	5.64[ab]	5.48[a]	6.05[c]	<0.0001
35 d of age					
Volume–weighted mean (µm)	25.10[a]	31.62[a]	46.19[b]	39.76[b]	<0.0001
Uniformity	2.45[a]	2.86[ab]	4.34[c]	3.31[b]	<0.0001
Specific surface area (m^2/g)	1.063[c]	1.058[bc]	1.020[b]	0.972[a]	<0.0001
Surface–weighted mean (µm)	5.73[a]	5.77[a]	5.96[a]	6.26[b]	<0.001

[1]Row means with different superscripts are statistically different

the gizzard to the duodenum and reflux to the proventriculus. An extended retention time of digesta in the gizzard for mechanical digestion of large particles may also increase microbial growth and the secretion of pH–modifying substances such as lactate, hence influencing digestive enzyme activity.

Sorghum particle size seems to influence digesta pH in the upper tract regardless of processing type, and this trend seems to strengthen with age. The pH of gizzard contents was influenced by feed texture to the extent that gizzard pH was reduced and duodenal pH was increased for WS compared to HM1. This is in contrast to other studies in which there has been no effect of feed form or texture on the pH of gizzard contents (Nir *et al*. 1995; Hetland *et al*. 2002). However, Nir *et al*. (1995) found a significant reduction in pH of proventriculus content with roller–milled wheat or sorghum compared to that with grains ground using a hammer–mill. Finely ground feed (HM1) reduced duodenal pH compared to WS. Taylor and Jones (2004) also observed a reduction of pH in the duodenum with fine feed, which was eliminated by feeding whole barley (200 g/kg) in a sorghum diet. As reported by Taylor and Jones (2004), Appleby *et al*. (1992) observed that lower duodenal pH may reduce the activity of amylolytic enzymes and the ability of the jejunum and ileum to absorb nutrients.

The present study is the first to examine whole sorghum. Reports on the effects of whole grain are equivocal; some studies show positive effects on performance and others show negative effects. By 35 d of age, bodyweight and cumulative feed consumption were not significantly different between treatments. In the present study, whole sorghum decreased 35–d bodyweight compared grain milled to an intermediate particle size. This is in contrast to many studies, in which whole grains such as barley (Svihus *et al*. 1997) increased bodyweight. As sorghum is a hard, vitreous grain, it is possible more energy is needed to grind whole sorghum in the gizzard than other grains, reducing the amount of energy available for growth.

The specific surface area of the roller–milled grain was lower than that of the hammer–milled grain of equivalent mean volume before pelleting. Therefore, the higher specific surface area of digesta particles from HM3 and RM0.15 birds at 21 d and that of WS birds at 35 d may be indicative of a change in the ability to process feed corresponding to organ development and age. It is possible that rolling sorghum improves the disruption of starch granules and protein matrices that bind starch, enabling more efficient use of the grain. Duodenal particle size was reduced by whole sorghum compared to that of all other treatments at 35 d. This is in contrast to the findings of Hetland *et al*. (2002), in which low inclusion levels of whole grain (wheat, oats and barley) resulted in a small duodenal particle sizes, and high levels (as in the current experiment) resulted in larger duodenal particle sizes.

There was no visible enteric disease associated with pathogens evident on dissection of the birds. In light of the pH differences associated with different particle sizes, further study of the effect of feed particle size on microbial activity is needed. The influence of feed particle size on digestive tract health and function and its relationship to microbial populations in the gut may become increasingly important as the use of antibiotic growth promotors and anticoccidials/antiprotozoals is reduced.

Conclusions

Roller–milling sorghum can improve efficiency of male broilers. Digestive tract health and AME_n is improved by whole sorghum relative to milled sorghum, although gut health does not necessarily result in heavier or more efficient birds. Improved gut development and health associated with pelleted diets containing whole grains may improve digestibility of nutrients and bird health.

Acknowledgements

The assistance of the Agricultural University Centre for Feed Technology, the Department of Animal and Aquacultural Sciences, NLH, Tim Walker and Bartter Enterprises, Australia, and the Australian Poultry Cooperative Research Centre is greatly appreciated.

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