



The effect of age of introducing whole sorghum grain on performance of broiler chickens

M. Mabelebele^{1,5}, R.M. Gous², H. Massey O'Neil³ and P.A. Iji⁴

¹ University of South Africa, Department of Agriculture and Animal Health, Christiaan de Wet Rd & Pioneer Ave, 1724, Rooderpoort, South Africa

² University of KwaZulu Natal, 31 Golf Rd, Scottsville, 3201, Pietermaritzburg, South Africa

³ AB Vista, Woodstock Ct, SN8 4AN, Marlborough, United Kingdom

⁴ Fiji National University, Kings Rd, 7222 Nasinu, Fiji

KEY WORDS: broiler chickens, digestibility, sorghum, whole grain feeding, visceral organs

Received: 10 February 2020
Revised: 15 April 2020
Accepted: 10 June 2020

⁵ Corresponding author:
e-mail: mabelebelem@gmail.com

ABSTRACT. The aim of this study was to assess the influence of age of whole sorghum grain introduction on productivity of male broiler chickens. In total, 324 one-day-old broiler chickens were assigned in a completely randomized design to 3 treatments (age of introduction of whole sorghum grain: 0, 11 and 25 days) with 9 replicates in each. Animals were offered 50% pre-pelleted whole sorghum at different growing ages. Body weight and feed intake were measured on a pen basis at 10, 25 and 35 day of age, and feed conversion ratio (FCR) was calculated. Birds introduced to whole sorghum grain feeding from day 0 and from 25 day of age, at 35 day of age were heavier and had better FCR ($P < 0.05$) than those to which whole grain was introduced from day 11. The relative visceral organ weights, meat parts yield, meat colour and pH were not influenced ($P > 0.05$) by the age of introduction of whole sorghum. The digestibility of gross energy, crude protein and starch were also not affected ($P < 0.05$). The age of introduction influenced certain performance parameters in broiler chickens. So, early feeding whole grain (at post-hatch) marginally improved body weight and FCR in broiler chickens.

Introduction

Inclusion of whole grain in poultry feeds has been practised for many years. This feeding method is based on the hypothesis that whole grains could improve bird health and gizzard function (Gabriel et al., 2006; Biggs and Parsons, 2009). Interest in increasing the size and activity of the gizzard through feeding the whole grain has developed from research reports that showed improved morphology of the intestinal tract (Taylor and Jones, 2004), which in turn enhances nutrient digestibility and utilization (Hetland et al., 2003). As a result, this practice is currently receiving renewed attention all over the world.

For many researchers, the age of animal in which whole grains can be firstly introduced into the feeding programme is the point of concern. The main problem with introducing whole grains to newly hatched chicks is the kernel size (Biggs and Parson, 2009) therefore it is suggested to use it by at least 5 day of age and up to 11–14 day of age (Plavnik et al., 2002; Hetland et al., 2003; Svihus et al., 2004). However, in some studies the whole grain was offered from the moment of hatch (Wu and Ravindran, 2004; Wu et al., 2004; Singh, 2013; Mabelebele et al., 2018) whilst in others the introduction was delayed to as late as 24 day of age (Uddin et al., 1996; Svihus et al., 2004).

Mostly whole grain feeding comprises the usage of barley (Biggs and Parsons, 2009), maize (Singh et al., 2014) and particularly wheat (Svihus et al., 2004; Wu et al., 2004). Only in very few studies sorghum was used (Fernandes et al., 2013; Moss et al., 2017). The reason for this fact might be due to the misconceptions related to poor growth performance associated with feeding commercial chickens sorghum-based diets. An attribute that favours the use of sorghum as a whole-grain supplement is its small kernel size, which allows for feeding it to young birds without difficulty.

Moreover, many areas in the world are not self-sufficient in grain production, the import is needed there. Maize grain prices, therefore, have remained high and will likely increase in the future. Thus, there is a necessity to find suitable feed sources that can potentially provide the same nutrients as maize. The use of feed ingredients such as grain sorghum in the poultry industry seems to be increasing due to a variety of factors. Conventional feed ingredients are more expensive and are not readily available to producers in all locations. Sorghum can be produced economically in adverse climatic conditions such as very hot and dry (Selle et al., 2010). Thus, an inexpensive cereal grain in a cost-effective feeding strategy would probably be the future of the poultry industry.

The thousand kernel (1000 TKW) weight, which is a measure of seed size of maize, wheat and sorghum, is 270–380 g, 38–44 g and 20–33 g, respectively. Thus, the purpose of this study was to evaluate the influence of age of introduction of whole sorghum grain (WSG) to the diet on productivity and nutrient digestibility in broiler chickens.

Material and methods

Experimental design, treatments and diets.

The feeding study was conducted on 324-day old chicken Ross 308 assigned to 27 cages (9 replications per treatment). The ages of introduction of whole sorghum were: 0, 11 and 25 day of age. The sorghum used in this study was supplied from local suppliers in Armidale (Australia). The colour of the selected sorghum grains used in the current study was red, with a thousand kernel weight of 33 ± 2 g, as an indicator of the grain size. The physical and chemical composition of the sorghum and diets was determined prior to formulating the experimental diets (Table 1). All feeds were formulated according to the specifications recommended by Aviagen (2014). Diets were offered to 324-day-old male Ross 308 broiler chicks (initial weight,

Table 1. Ingredients and nutrient composition of experimental diet

Indices	Amount
Ingredients, g/kg	
sorghum	673
SBM, Arg 2400-45.2	156
canola ml solvent 2000-37	50.0
meat meal 59	87.3
canola oil	12.8
limestone	2.36
dicalcium phosphate 18P/21Ca	0.01
xylanase powder 100 g/mt	0.10
quantum blue 5G (100 g)	0.10
salt	0.597
Na bicarbonate	1.88
UNE VM premix 2 kg/mt ¹	2.00
choline Cl 70%	1.28
L-lysine HCl 78.4	4.04
DL-methionine	1.81
L-threonine	1.98
titanium oxide	5.00
Chemical composition, g/kg	
AME, MJ/kg	12.97
crude protein	215
crude fibre	24.47
crude fat	45.5
digestible	
arginine	11.1
lysine	11.5
methionine	4.7
methionine + cysteine	7.0
leucine	9.0
tryptophan	1.7
calcium	8.7
available P	4.35
potassium, g/kg	2.3
chloride, g/kg	1.6
sodium, g/kg	1.6
choline, mg/kg	1600
Analysed values of sorghum	
dry matter, %	93
gross energy, MJ/kg	17.6
crude protein, g/kg	81.1
starch, g/kg	503
fat, g/kg	31.3
calcium, mg/kg	100.1
Total P, mg/kg	2210
Condensed tannin (mg of catechin equivalent/100 mg)	0.1

¹ vitamin contained per kg of diet, µg: retinol acetate 4500; mg: cholecalciferol 50, tocopheryl acetate 40.0, menadione 5, thiamine 3, riboflavin 6, pyridoxine 5, cobalamin 0.03, nicotinic acid 30, biotin 0.1, calcium d-pantothenate 12, folic acid 1, choline chloride 400, manganese 80, iron 35, zinc 50, copper 5, iodine 2, cobalt 0.4, selenium 0.15 assured

41 ± 3 g) acquired from a local hatchery (Baiada Poultry Pty. Ltd, Tamworth, Australia). In experimental diets 500 g milled sorghum/kg was replaced (at proper time) with the same amount of whole sorghum. All feeds were mixed and cold-pelleted at the University of New England (Armidale, Australia).

Pellet quality was measured using a Seedburo durability tester (Seedburo Equipment Company, Chicago, IL, USA). A representative sample of pellets weighing 500 g was screened, tumbled for 10 min and re-screened to weigh the whole pellet samples. The pellet durability index was calculated by dividing the weight of the whole pellets by 500 and multiplying by 100.

Initial brooding temperature was 33 °C, which was gradually reduced to 24 ± 1 °C at 19 day of age and maintained to the end of the trial. Access to feed and water was provided *ad libitum* over the trial period. The Animal Ethics Committee of the University of New England (UNE), approved the experiment with the number AEC15-082. All management and procedures in this study were carried out in strict accordance with the requirements of the UNE Code of Practice for Experimental Animals, the Australian Code of Practice for the Care and Use of Animals for Scientific Purposes (2004), the New South Wales (NSW) Animal Research Act (1985) and NSW Animal Research Regulation (2005).

Growth performance

Body weight (BW) and feed intake (FI) were recorded on a cage average basis at 10, 25 and 35 day of age. Mortality in each cage was recorded daily as it occurred until the end of the trial, and feed conversion ratio (FCR) was corrected for mortality. On days 14 and 28, birds were weighed individually, and flock uniformity was calculated using the following formula:

$$\text{flock uniformity \%} = 100 - \left[\frac{\text{standard deviation (g)}}{\text{average body weight (g)}} \times 100 \right]$$

Two birds were randomly selected from each cage at 35 day of age, weighed and humanely killed by cervical dislocation for measurement of visceral organ weights. The proventriculus plus gizzard with contents, small intestine (the region from the distal end of gizzard to one cm above the ileo-caecal junction) with contents, pancreas, spleen, liver, heart and bursa of Fabricius were weighed. Carcass yield of the chickens was determined, and the measurements included carcass weight, breast meat yield, drum and thigh weights. Breast meat samples were also collected at 35 day of chickens' age to determine meat pH and colour. Meat pH was measured 30 min

post-mortem using a calibrated (standard buffers at pH 4.0 and 7.0) Crison 506 portable pH meter (Crison, Barcelona, Spain) whereas meat colour was measured using a colour guide 45°/0° colorimeter (catalogue no: 6805; BYK-Gardner, Columbia, MD, USA).

Coefficient of apparent ileal digestibility determination

At the end of finisher phase, on day 3, two birds were randomly selected and slaughtered, and a portion of the small intestine extending from Meckel's diverticulum to a point 40 mm proximal to the ileo-caecal junction (ileum) was carefully excised. The contents of the lower half of the ileum were collected by gentle flushing with distilled water into plastic containers. Digesta samples were pooled within a cage, freeze-dried, ground to pass through a 0.5-mm screen size and stored in airtight containers at -4 °C until laboratory analysis. Digesta and feed samples were analysed for dry matter, titanium (Ti), nitrogen (N), starch and energy contents. The nitrogen content of the feed and ileal digesta was determined according to the Dumas technique of combustion using a LECO FP-2000 automatic nitrogen analyser (LECO Corp., St Joseph, MI, USA) and following the method reported by Sweeney (1989). Starch and gross energy contents of the diets and ileal digesta were measured by the methods described by AOAC International (2010). The concentration of TiO₂ in the feed and ileal digesta was measured in line with methods described by Short et al. (1996). The concentration of TiO₂, measured in mg/ml, was calculated from the standard curve and converted to mg/g of the sample.

Determination of apparent metabolizable energy (AME) and nitrogen retention

Feed intake and excreta output of each cage were collected and measured for four days between days 32 and 35. Total excreta was pooled within each cage, thoroughly mixed and sub-sampled. The sub-samples were then oven-dried at 80 °C in a draft oven, ground to pass through a sieve (0.5-mm) and stored at -4 °C until further analysis. The following formulae were used to calculate apparent metabolizable energy (AME) and N-retention:

1. AME (MJ/kg) = [(feed intake × GE_{diet}) - (excreta output × GE_{excreta})] / feed intake × GE_{diet},
2. N-retention (%) = 100 × [(feed intake × N_{diet}) - (excreta output × N_{excreta})] / feed intake × N_{diet}.

Statistical analysis

The data were statistically assessed by one-way analyses of variance in SAS version 9.4 software programme (SAS, 2010). The Duncan's multiple range test was used to compare means where the effect of treatments was significant at the 5% level of probability.

Results

The effects of age of introduction of whole sorghum on FI, BW and FCR from day 1 to 35 are given in Table 2. Over the entire growing period to 35 day of age FI was similar ($P > 0.05$) in groups where whole sorghum was introduced at either 0, 11 and 25 day of age. Birds fed whole grain from day 1 of age at 35 day of age, and those with introduced whole grain from 25 day of age were heavier ($P < 0.05$) than those which have whole grain introduced at day 11 of age. Similarly, birds that have whole grain introduced to the diet at 1 and 25 day of age had better ($P < 0.05$) FCR at day 35 in comparison to those fed whole grain from day 11 of age. Age of introduction did not affect ($P > 0.05$) flock uniformity of broiler chickens at 35 day of age (Figure 1). However, flock uniformity tended to increase with delay in introduction of whole sorghum grain.

Table 2. Effect of age of introduction of whole sorghum on feed intake (FI), body weight (BW) and feed conversion ratio (FCR) at 35 day of age

Treatment	FI, g/bird	BW, g/bird	FCR
Age of introduction			
day 0	3600	2242 ^a	1.61 ^{ab}
day 11	3548	2136 ^b	1.66 ^a
day 25	3482	2250 ^a	1.54 ^b
SEM	59.7	30.2	0.028

^{a,b} – means in the same column with different superscripts are significantly different at $P < 0.05$; SEM – standard error of the mean; mean body weight at day 0 was 40 g/bird, day 11 – 330.45 g/bird and day 25 – 1576.38 g/bird; each value represents the mean of nine replicates (twelve birds/pen)

The age of introduction had no effect ($P > 0.05$) on relative visceral organ weights at 35 day of age (Table 3) except for the liver weight. Livers of birds that were offered whole grain from hatch and from 11 day of age were heavier ($P < 0.05$) than livers of birds fed whole grain from 25 day of age. Numerically, the weight of proventriculus + gizzard relative to body weight of birds that were offered whole sorghum grain from an earlier age tended ($P > 0.05$) to be higher.

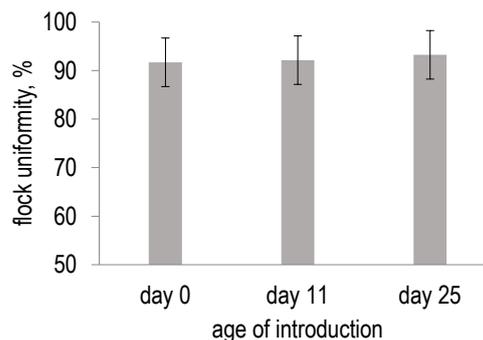


Figure 1. Effect of age of introduction of whole sorghum grain on flock uniformity of broiler chickens, %

Table 3. Effect of age of introduction of whole sorghum on relative organ weights (g/100 g body weight) of broiler chickens at 35 day of age

Treatment	P+Giz ¹	Small intestine	Pancreas	Liver	Heart	Spleen	Bursa
Age of introduction							
day 0	2.70	4.54	0.19	2.90 ^{ab}	0.62	0.26	0.08
day 11	2.65	4.49	0.21	2.97 ^a	0.69	0.27	0.08
day 25	2.54	4.27	0.20	2.74 ^b	0.62	0.26	0.09
SEM	0.10	0.12	0.05	0.07	0.02	0.009	0.04

^{a,b} – means in the same column with different superscripts are statistically different at $P < 0.05$; SEM – standard error of the mean; ¹P+Giz proventriculus and gizzard weight; each value represents the mean of nine replicates (twelve birds/pen)

The meat parts yield, colour and pH of broiler chickens offered whole sorghum grain at different ages are shown in Table 4. The age of introduction did not affect ($P > 0.05$) carcass weight or weight of breast, thighs or drumsticks of broiler chickens at 35 day of age. Meat pH and colour of breast muscles were similar ($P > 0.05$) regardless of age from which whole sorghum was introduced to bird diets.

Table 4. Influence of age of introduction of whole sorghum on broiler chicken meat parts yield (g), pH and colour at day 35 of age

Treatment	Carcass weight	Breast	Thigh	Drumstick	pH	L*	a*	b*
Age of introduction								
day 0	1705	407	202	190	5.86	51.468	2.6	6.31
day 11	1673	392	204	186	5.88	53.678	1.9	6.70
day 25	1552	402	200	186	5.84	53.868	1.6	6.89
SEM	60.3	21.2	7.5	6.4	0.1	1.0	0.9	0.1

^{a,b} – means in the same column with different superscripts are significantly different at $P < 0.05$; SEM – standard error of the mean; * (lightness) a* (redness) b* (yellowness); each value represents the mean of nine replicates (twelve birds/pen)

The age of introduction of the whole grain to the diet did not affect ($P > 0.05$) either starch, gross energy (GE) or crude protein (CP) digestibility (Table 5). The effects of age of introduction of whole sorghum grain on AME and AME of the cereal and

Table 5. Influence of age of introduction of whole sorghum on gross energy (GE), starch and crude protein (CP) digestibility in broiler chickens

Treatment	GE	CP	Starch
Age of introduction			
day 0	0.77	0.75	0.83
day 11	0.76	0.75	0.84
day 25	0.75	0.76	0.82
SEM	0.0197	0.0193	0.0110

SEM – standard error of the mean; each value represents the mean of nine replicates (twelve birds/pen)

Table 6. Effect of age of introduction of whole sorghum on AME, AME of sorghum and nitrogen retention of broiler chickens

Treatment	AME (digesta), MJ/kg	AME (cereal), MJ/kg	N-retention, %
Age of introduction			
day 0	16.34	17.35	74.52
day 11	16.48	17.29	70.46
day 25	16.43	17.30	72.77
SEM	0.149	0.158	1.646

AME – apparent metabolizable energy; SEM – standard error of the mean; each value represents the mean of nine replicates (twelve birds/pen)

N-retention by the broilers are presented in Table 6. Birds that were offered whole grain from hatch and from day 11 of age exhibited similar ($P > 0.05$) AME values. The AME (cereal) of sorghum was also similar ($P > 0.05$) for birds offered whole grain from hatch and from 11 day of age. The age of introduction of whole sorghum did not influence ($P > 0.05$) N-retention.

Discussion

The pellet durability index reported in the current study was 90%; moreover, a non-tannin sorghum variety with 16.8 MJ/kg GE value and 10.9% CP content was used. The performance of broiler chickens subjected to the introduction of whole sorghum grain was evaluated in the present study. All broilers were thus subjected to whole grain feeding for the whole or part of their growing period. The age at which whole sorghum was introduced had variable effects on BW and FCR. The earliest introduction (at hatch) and the latest introduction (at 25 day of age) had increased animal BW and improved FCR in comparison to animals having introduced whole grain from 11 day of age. When Biggs and Parsons (2009) introduced whole sorghum from hatch at inclusion levels of 10 and 20% no effect was observed when compared to a maize-soybean feed. Mabelebele

et al. (2018) reported that from hatch an inclusion level of up to 75% resulted in no detrimental effects on performance of broiler chickens. In a study by Gabriel et al. (2008) it was indicated that whole-wheat inclusion at 22 and 29 day of age improved FCR as compared to the birds that were introduced whole-wheat earlier. This improvement at a later stage was due to the adaptation period to whole grain feeding. It is not clear why whole sorghum feeding in the current study did not improve some growth variables at 11 day of age. It is, however, assumed that whole grain feeding introduced later into bird diet results in improved productivity (Hetland et al., 2002; Wu and Ravindran, 2004; Wu et al., 2004) in comparison to an earlier introduction. This is likely because the gizzard of newly hatched chicks is not fully developed and is unable to grind large particles. Further, the grinding process in the gizzard requires energy that is diverted from growth.

Additional reasons for the adoption of whole grain feeding regimes include the justification that whole grain feeding improves ‘gut integrity’ in broiler chickens. Arguably, relative gizzard weights are an indicator of gut integrity (Truong et al., 2017). Exposing chickens to whole grain at hatch with the intention of improving bird health and nutrient utilization by increasing gizzard size did have some effect in this trial. Gizzard weight, in proportion to whole BW, numerically tended to increase with the earliest introduction of whole sorghum grain. It, therefore, remains unclear as to why chickens offered whole sorghum grain from 11 day of age had higher liver weight than those offered whole sorghum from hatch and 25 day of age. These results are contrary to most of the reports, in which it is stated that whole grain inclusion increases the gizzard and small intestine weights (Thomas and Ravindran, 2008; Biggs and Parsons, 2009; Fernandes et al., 2013). The landmark response to whole grain feeding is suggested to increase relative gizzard weights. It was thus, assumed on the basis of the data from earlier studies (Jones and Taylor, 2001; Taylor and Jones, 2004; Wu et al., 2004), that pre-pellet whole grain addition would not generate comparable increases in gizzard mass probably because pelleting ‘crushes’ whole grain. Moreover, whilst the majority of research reports agree that whole grain feeding improves gut integrity, it should be stressed that gizzard mass responses to whole grain inclusions are extremely inconsistent. This might depend on factors such as grain type used in whole grain feeding.

The age of introduction of whole grain did not affect the meat parts yield and flock uniformity of broiler chickens used in the current study. The values of the meat colour, especially the lightness, were seen to be around those that were observed in maize. It was thought that sorghum-based diets could affect the meat colour and pH of broiler chickens due to the lack of pigments like those found in maize. However, Garcia et al. (2013) reported the luminosity values of the breast meat from broiler chickens fed maize-based feeds to be like those that were offered sorghum-based feeds. The meat pH in this study was also not affected by the age of introduction of whole sorghum.

It is assumed that exposing chicks to whole grains at younger ages (such as immediately after hatching) may increase the beneficial effects on nutrient digestibility; however this was not in the case of the current study. It has been suggested that whole grain feeding increases nutrient digestibility (Svihus et al., 1997; Jones and Taylor, 2001; Singh, 2013). In the current study, the digestibility of GE, starch and CP of chickens offered whole grain from hatch and from 11 day of age was similar. It is unclear why the birds offered whole sorghum grains at all ages of introduction had similar AME and N-retention. This was expected as the gizzard relative weights were similar for all birds irrespective of their age of introduction to whole sorghum grain. Moreover, the N-retention values for all the examined ages of whole sorghum grain introduction observed in the current study were within the ranges reported by Liu et al. (2016) on three sorghum varieties. Perhaps, it will be reasonable to acknowledge that any improvements in nutrient utilisation and digestibility observed in whole grain feeding studies, is due to post-pelleting as opposed to pre-pelleting.

Conclusions

Whole sorghum grain in the amount of 50% of the diet can be included into chicken diets and offered from hatch without any adverse effects on performance. It can therefore, be concluded that introducing whole grain to birds from hatch may improve their performance throughout the growing period.

Acknowledgments

The authors would like to acknowledge and appreciate the funding from National Research Foundation (NRF- GUN no: 97095), South Africa and AB Vista Marlborough, UK for making this work possible.

References

- AOAC International, 2010. Official Methods of Analysis of AOAC. 18th Edition. 3rd Revision. Gaithersburg, MD (USA)
- Aviagen, 2014. Ross 308 Broiler Chicken's Performance Objectives. Aviagen. Huntsville, AL (USA), www.aviagen.com
- Biggs P., Parsons C.M., 2009. The effects of whole grains on nutrients digestibilities, growth performance, and caecal short-chain in young chicks fed ground corn-soybean meal diets. *Poult. Sci.* 88, 1893–1905, <https://doi.org/10.3382/ps.2008-00437>
- Fernandes E.A., Pereira W.J.S., Hackenhaar L., Rodrigues R.M., Terra R., 2013. The use of whole grain sorghum in broiler feeds. *Braz. J. Poult. Sci.* 15, 217–222, <https://doi.org/10.1590/S1516-635X2013000300008>
- Gabriel I., Mallet S., Leconte M., 2006. Differences in the digestive tract characteristics of broiler chickens fed on complete pelleted diet or on whole wheat added to pelleted protein concentrate. *Br. Poult. Sci.* 44, 283–290, <https://doi.org/10.1016/j.anifeedsci.2006.01.004>
- Gabriel I., Mallet S., Leconte M., Travel A., Lalles J.P., 2008. Effects of whole wheat feeding on the development of the digestive tract of broiler chickens. *Anim. Feed Sci. Technol.* 142, 144–162, <https://doi.org/10.1016/j.anifeedsci.2007.06.036>
- Garcia R.G., Mendes A.A., Almeida Paz I.C.L., Komiyama C.M., Caldara F.R., Nääs I.A., Mariano W.S., 2013. Implications of the use of sorghum in broiler production. *Braz. J. Poult. Sci.* 15, 257–262, <https://doi.org/10.1590/S1516-635X2013000300013>
- Hetland H., Svihus B., Krogdahl Å., 2003. Effects of oat hulls and wood shavings on digestion in broilers and layers fed diets based on whole or ground wheat. *Br. Poult. Sci.* 44, 275–282, <https://doi.org/10.1080/0007166031000124595>
- Hetland H., Svihus B., Olaisen V., 2002. Effect of feeding whole cereals on performance, starch digestibility and duodenal particle size distribution in broiler chickens. *Br. Poult. Sci.* 43, 416–423, <https://doi.org/10.1080/00071660120103693>
- Jones G.P.D., Taylor R.D., 2001. The incorporation of whole grain into pelleted broiler chicken diets: production and physiological responses. *Br. Poult. Sci.* 42, 477–483, <https://doi.org/10.1080/00071660120070587>
- Liu S.Y., Truong H.H., Khoddami A., Moss A.F. et al., 2016. Comparative performance of broiler chickens offered ten equivalent diets based on three grain sorghum varieties as determined by response surface mixture design. *Anim. Feed Sci. Technol.* 218, 70–83, <https://doi.org/10.1016/j.anifeedsci.2016.05.008>
- Mabelebele M., Gous R.M., O'neil H.V.M., Iji P.A., 2018. Whole sorghum inclusion and feed form on performance and nutrient digestibility of broiler chickens. *J. Appl. Anim. Nutr.* 6, 1–8, <https://doi.org/10.1017/JAN.2018.3>
- Moss A.F., Sydenham C.J., Truong H.H., Liu S.Y., Selle P.H., 2017. The interactions of exogenous phytase with whole grain feeding and effects of barley as the whole grain component in broiler diets based on wheat, sorghum and wheat-sorghum blends. *Anim. Feed Sci. Technol.* 227, 1–12, <https://doi.org/10.1016/j.anifeedsci.2017.02.013>
- Plavnik I., Macovsky B., Sklan D., 2002. Effect of feeding whole wheat on performance of broiler chickens. *Anim. Feed Sci. Technol.* 96, 229–236, [https://doi.org/10.1016/S0377-8401\(01\)00321-2](https://doi.org/10.1016/S0377-8401(01)00321-2)
- SAS Institute, 2010. The SAS System version 9.4. Statistical Analysis System Institute Inc. Cary, NC (USA)
- Selle P.H., Gill R.J., Downing J.A., 2010. The vulnerability of sorghum to 'Moist-Heat'. In: Proceedings of the 21st Australian Poultry Science Symposium on Broiler Nutrition. Sydney (Australia), APSS publication No. 21, 68–71

- Short F.J., Gorton P., Wiseman J., Boorman K.N., 1996. Determination of titanium dioxide added as an inert marker in chicken digestibility studies. *Anim. Feed Sci. Technol.* 59, 215–221, [https://doi.org/10.1016/0377-8401\(95\)00916-7](https://doi.org/10.1016/0377-8401(95)00916-7)
- Singh Y., 2013. Whole grain inclusion in poultry diets: effects on performance, nutrient utilisation, gut development, caecal microflora profile and coccidiosis challenge. PhD Thesis. Institute of Veterinary, Animal and Biomedical Sciences. Massey (New Zealand)
- Singh Y., Amerah A.M., Ravindran V., 2014. Whole grain feeding: methodologies and effects on performance, digestive tract development and nutrient utilisation of poultry. *Anim. Feed Sci. Technol.* 190, 1–18, <https://doi.org/10.1016/j.anifeedsci.2014.01.010>
- Svihus B., Juvik E., Hetland H., Krogdahl Å., 2004. Causes for improvement in nutritive value of broiler chicken diets with whole wheat instead of ground wheat. *Br. Poult. Sci.* 45, 55–60, <https://doi.org/10.1080/00071660410001668860>
- Svihus B., Newman R.K., Newman C.W., 1997. Effect of soaking, germination, and enzyme treatment of whole barley on nutritional value and digestive tract parameters of broiler chickens. *Br. Poult. Sci.* 38, 390–396, <https://doi.org/10.1080/00071669708418008>
- Sweeney R.A., 1989. Generic combustion method for determination of crude protein in feeds: a collaborative study. *J. Assoc. Off. Anal. Chem.* 72, 770–774, <https://doi.org/10.1093/jaoac/72.5.770>
- Taylor R.D., Jones G.P.D., 2004. The incorporation of whole grain into pelleted broiler chicken diets. II. Gastrointestinal and digesta characteristics. *Br. Poult. Sci.* 45, 237–246, <https://doi.org/10.1080/00071660410001715849>
- Thomas D.V., Ravindran V., 2008. Effect of cereal type on performance, gastrointestinal tract development and intestinal morphology of the newly hatched chick. *Br. Poult. Sci.* 45, 46–50, <https://doi.org/10.1080/00071660802213467>
- Truong H.H., Moss A.F., Liu S.Y., Selle P.H., 2017. Pre- and post-pellet whole grain inclusions enhance feed conversion efficiency, energy utilisation and gut integrity in broiler chickens offered wheat-based diets. *Anim. Feed Sci. Technol.* 224, 115–123, <https://doi.org/10.1016/j.anifeedsci.2016.12.001>
- Uddin M.S., Rose S.P., Hiscock T.A., Bonnet S., 1996. A comparison of the energy availability for chickens of ground and whole grain samples of two wheat varieties. *Br. Poult. Sci.* 37, 347–357, <https://doi.org/10.1080/00071669608417866>
- Wu Y.B., Ravindran V., 2004. Influence of whole-wheat inclusion and xylanase supplementation on the performance, digestive tract measurements and carcass characteristics of broiler chickens. *Anim. Feed Sci. Technol.* 116, 129–139, <https://doi.org/10.1016/j.anifeedsci.2004.02.011>
- Wu Y.B., Ravindran V., Hendricks W.H., 2004. Influence of exogenous enzyme supplementation on energy utilisation and nutrient digestibility of cereals for broilers. *J. Sci. Food Agric.* 84, 1817–1822, <https://doi.org/10.1080/00071660410001668897>