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Whole grain in turkey nutrition. Part 1: Gastrointestinal development and function

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Currently whole grain is incorporated into poultry diets to lower production costs, stimulate the development of the gizzard, prevent potentially pathogenic bacteria from entering the intestine and improve the growth rate and feed conversion of birds. The present review discusses the results of experiments performed on turkeys where whole grain (WG) or large-sized feed particles were incorporated into diets with the use of different processing methods (with pre- or post-pelleting inclusion) and in different quantities. The results of recent experiments indicated that, within the first month, gizzard weight increased significantly when the size of feed particles was increased from 380 to 806 mm, or when turkey diets were supplemented with 20% WG. In older birds, gizzard weight increased when the WG content of pelleted diets exceeded 20%. Dietary dilution with WG did not cause significant changes in the development or functionality of the small intestine, including mucosal enzyme activity. The presence of WG in the diet increased the amount of coarse particles in the digesta leaving the gizzard, which did not lower the apparent digestibility of dry matter and crude fibre or nitrogen retention. The inclusion of WG in turkey diets led to a decrease in the counts of *Clostridium spp.*, *Campylobacter* and/or *Escherichia coli*, and an increase in the counts of *Lactobacillus spp.* and/or *Bifidobacterium spp.* in the caecal digesta. However the effect of WG inclusion in turkey diets on gut morphology has been investigated in only a few studies to date, and the results are inconclusive.

Keywords: feed form; whole grain; gastrointestinal tract; turkey

Introduction

The integrity and functionality of the gastrointestinal tract (GIT) are a prerequisite for achieving efficient performance in poultry production, in particular since the European Union banned the use of antibiotic growth promoters in animal feed (Choct, 2009).

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Nutritionists and feed manufacturers have long been searching for new strategies to promote, maintain and restore gut health so as to ensure the stability and safety of egg and poultry meat production. One of the most promising research areas is the influence of whole grain inclusion in poultry diets on GIT development and the growth performance of birds (Amerah *et al.*, 2011; Singh *et al.*, 2014a). Some studies have reported that feeding whole grains to poultry improves gut health and the welfare of birds (Ferket, 2000; Banfield and Forbes, 2001; Gabriel *et al.*, 2003a). This is an important consideration in view of the increasing incidence of wet litter syndrome caused by various insufficiently investigated nutritional factors (Francesch and Brufau, 2004: Mayne *et al.*, 2007).

Whole grain, primarily wheat grain, is incorporated into poultry diets to stimulate the development of the gizzard (Engberg *et al.*, 2004; Amerah *et al.*, 2007; 2008), prevent potentially pathogenic bacteria from entering the intestine (Engberg *et al.*, 2004) and improve the growth rate and feed conversion of birds (Plavnik *et al.*, 2002; Ravindran *et al.*, 2006; Biggs and Parsons, 2009; Amerah *et al.*, 2011). However, research findings published to date only partially confirm these expectations associated with feeding whole grains to broiler chickens. Experiments involving turkeys remain scarce, and their results are inconsistent and inconclusive.

Nutrient concentrations are significantly higher in diets for young turkeys in comparison with diets for broiler chickens (NRC, 1994). Thus, growing turkeys (up to 12 weeks of age) may be more sensitive to dietary dilution with whole grains and unbalanced daily rations offered free-choice. The rearing period is longer in turkeys (up to 24 weeks) than in chickens, which allows the use of different strategies of whole grain feeding. In view of the above, the objective of this review article was to summarise the findings of published studies investigating the response of the gastrointestinal tract of turkeys to feeding of whole grains, which are fewer than experiments involving chickens.

Effect of dietary whole grain on gizzard development and function

The structure and function of the gizzard in poultry have been discussed in numerous studies conducted mostly on chickens, and their results have been summarised in recent scientific papers (Svihus, 2011; 2014; Gjevre *et al.*, 2013; Singh *et al.*, 2014a). Similar experiments involving turkeys are scarce and rather obsolete (Duke *et al.*, 1984; Duke, 1992). One of the topical issues in turkey research is gizzard erosion and ulceration (Kaldhusdal *et al.*, 2012; Gjevre *et al.*, 2013).

The gizzard contains strongly myolinated muscles and has a koilin layer, which will aid in the grinding process due to its sand-paper-like surface (Svihus, 2014). As discussed in detail in a review article by Singh *et al.* (2014a), chickens raised under conventional feeding regimes where WG is ground before incorporation into feed showed that the gizzard can be relatively underdeveloped because finely ground, pelleted diets are rapidly moved down the gut. As a result, within 30 min of feeding, considerable amounts of feed bypass the gizzard and enter the small intestine (Svihus *et al.*, 2002). Feed material may more easily bypass the gizzard when this region is empty. In an experiment where growing turkeys were fed a finely ground diet after a 10-h fasting period, the small intestine was filled with feed within 25 min from commencement of feeding (Jackson and Duke, 1995).

It is believed that feeding WG to poultry improves gut health (Ferket, 2000; Banfield and Forbes, 2001; Gabriel *et al.*, 2003a) and reduces the incidence of gizzard erosion and ulceration in chickens and turkeys (Kaldhusdal *et al.*, 2012; Gjevre *et al.*, 2013). The latter condition is caused by a number of predisposing and environmental factors, and

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one of the prevention strategies relies on a diet rich in insoluble fibre from cereals (Kaldhusdal *et al.*, 2012).

The results of recent experiments revealed that a relatively empty gizzard was heavier in broilers fed mash than in broilers fed crumbled or pelleted diets (Serrano *et al.*, 2013), and gizzard tissue weight was considerably increased by the inclusion of coarse ground corn in mash (Xu *et al.*, 2015). In broiler chickens, gizzard development may be stimulated by WG inclusion in the diet (Engberg *et al.*, 2004; Gabriel *et al.*, 2008). In a comprehensive review of gizzard functionality, Svihus (2011) concluded that at least 20% of grain particles larger than 1.5-2.0 mm in size in the diet are needed to stimulate gizzard development in broilers. Such recommendations for formulating turkey diets have not been established. The results of studies investigating the effect of the physical form of feed, including diet dilution with WG, on gizzard development in turkeys are summarised in *Table 1*.

Table 1 Influence of WG or large-sized feed particle on gizzard development in turkeys.

Reference	Short protocol design	Main results
Bennett *et al.* (2002)	Crumbled (CB) or whole barley (WB) in the amount of 5, 20 and 50% of the diet recommended for birds at 0 - 12, 13 - 18 and 19 - 32 days of age, respectively	At 32 days, relative gizzard weight was significantly higher in group WB *vs.* group CB, $P < 0.05$
Favero *et al.* (2012)	Experiment with a 2×3 factorial design with two forms of feed (crumbled and micropelleted) and three corn particle sizes (380, 606, 806 mm)	At 21 days, the differences in gizzard weight were as follows: crumbled diet > micropelleted diet, large particle size > small particle size, $P = 0.001$ in both cases
Konca *et al.* (2012)	WB or whole triticale (WT) in the amount of 9.1, 13.0 and 16.7% of the diet administered in weeks 4 - 8, 9 - 12 and 13 - 18, respectively	At 18 weeks of age, no differences ($P>0.05$) in absolute gizzard weight or relative gizzard weight were observed between groups
Jankowski *et al.* (2013b)	Ground and pelleted wheat (GW) replaced with increasing rates of whole wheat (WW) at 25, 50, 75 and 100% in two feeding periods of 5 - 8 and 9 - 12 weeks	Gizzard weight was as follows: W_0 - 8.40, W_{25} - 8.99, W_{50} - 10.1, W_{75} - 10.6, W_{100} - 12.0 g/kg BW, with a linear contrast, $P< 0.001$
Zdunczyk *et al.* (2013)	Control diet diluted with GW or WW, at a low and high dilution level (LW and HW, respectively), *i.e.* 5/15% and 12.5/22.5% in weeks 5 - 8 and 17 - 18, respectively	The difference in gizzard weight was as follows: WW > GW, $P = 0.001$ HW > LW, $P = 0.044$
Jankowski *et al.* (2014)	WW accounted for 20% of the daily ration, irrespective of total wheat content. Both diets were fed between 5 and 18 weeks	At 18 weeks of age, gizzard weight was similar in both groups, WW_0 - 5.2 and WW_{20} - 5.4 g/kg BW

In the experiment performed by Bennett *et al.* (2002), for the treatment where whole barley was introduced on day 0, gizzard pH decreased at 18 days of age, and gizzard weight increased at 32 days of age, in comparison with the group fed crumbled barley. Gizzard weight increased ($P>0.05$) in young turkeys (21 days of age) when a micropelleted diet was replaced with a crumbled diet, or a diet containing large-sized feed particles (Favero *et al.*, 2012). A similar effect was observed in older turkeys (five to

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12 weeks of age) in which higher dietary inclusion levels of WW led to a linear increase in gizzard weight (Jankowski *et al.*, 2013b). In other experiments performed on 18-week-old turkeys, the increase in gizzard weight was statistically significant when 20% WW was added to pelleted diets (Zdunczyk *et al.*, 2013), whereas the pre-pelleting inclusion of 20% WW had no effect on gizzard size (Jankowski *et al.*, 2014). The above results indicate that large-sized feed particles or WG may stimulate an increase in gizzard weight in turkeys provided that the WW content of diets exceeds 20% and the grain has not been pre-pelleted.

Effect of dietary whole grain on small intestine development and functionality

The majority of studies performed on chickens, whose results were summarised in a review article by Singh *et al.* (2014a), revealed no changes in the relative weight and length of intestinal segments when GW was replaced with WW. However, in some experiments, the substitution of WW for GW resulted in lower duodenal weight (Gabriel *et al.*, 2003b) or higher duodenal length (Taylor and Jones, 2004).

In most of the experiments presented in *Table 1* (Bennett *et al.*, 2002; Favero *et al.*, 2012; Konca *et al.*, 2012; Zdunczyk *et al.*, 2013; Jankowski *et al.*, 2014), WG had no effect on the development and function of the small intestine in turkeys. However, in some studies, WG inclusion in the diet significantly affected the viscosity of the small intestinal contents. Palander *et al.* (2005) reported that 50% whole barley (WB) in the basal diet increased jejunal viscosity in turkeys. A similar effect was noted in one of the experiments with turkeys, where the replacement of GW with WW caused with a linear increase in small intestinal viscosity (Jankowski *et al.*, 2013b).

It has been estimated that the mean retention time of digesta in the gizzard varies between 30 and 60 minutes (Svihus *et al.*, 2002; Svihus, 2014). It appears that larger-sized feed particles may be selectively retained in the gizzard (Hetland *et al.*, 2003), and that the grinding activity of the gizzard enhances in response to WG feeding, which increases the retention time of feed particles (Roche, 1981; Svihus, 2011). The results of experiments with broiler chickens indicate that WG inclusion had no effect on particle size distribution in the duodenal digesta (Svihus *et al.*, 1997; Hetland *et al.*, 2003), and that the digesta passing through the gizzard had a consistent particle size distribution, with the majority of particles being smaller than 40 μm regardless of the original feed structure (Hetland *et al.*, 2002).

Table 2 shows the results of a study that investigated the effect of a different WW content of the diet on feed particle size in the intestinal contents of growing turkeys. After four weeks of feeding, the size of feed particles that left the gizzard and reached the duodenal digesta was determined in turkeys aged eight weeks. It was found that an increased amount of whole grains in the diet resulted in a linear increase in particles larger than 2 mm ($P = 0.002$) and a linear decrease in particles ranging in size from 1 to 2 mm and smaller than 0.071 mm ($P = 0.001$ excluding particles ranging in size from 0.106 to 0.071 mm) in the duodenal digesta. These results were consistent with those of Amerah *et al.* (2007) who demonstrated that a high number of particles larger than 0.500 mm transited the duodenum without breaking down, when coarser feed was administered. The results of experiments on turkeys (Jankowski *et al.*, 2013a), as well as experiments on chickens (Svihus *et al.*, 1997; Hetland *et al.*, 2003; Svihus, 2011) indicated that feed with WW was effective in breaking down in the gizzard, however, the feed particles are bigger and coarser than those produced in the grinding process.

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Table 2 Feed particle size in the intestinal contents of growing turkeys fed diets with a different WW content[1] (Jankowski *et al.*, 2013a).

Particle size class (mm)[1]	Treatment[2]					P value for linear contrast
	WW_0	WW_{25}	WW_{50}	WW_{75}	WW_{100}	
> 2.0	0.770	0.764	0.777	0.831	0.842	0.002
2.0 - 1.0	0.622	0.603	0.500	0.559	0.323	<0.001
1.0 - 0.5	0.444	0.129	-0.006	0.136	-0.191	<0.001
0.5 - 0.25	0.032	-0.025	-0.490	-0.793	-0.770	<0.001
0.25 - 0.11	-0.025	0.131	-0.293	-0.632	-0.358	<0.001
0.11 - 0.07	0.146	0.268	0.162	-0.256	0.217	0.594
< 0.07	-0.690	-0.836	-0.976	-1.814	-1.763	<0.001

[1]The particle size distributions of diets and duodenal digesta (feed particle fraction - digesta particle fraction/feed particle fraction) were determined by wet sieving, as described by Lentle *et al.* (2006).
[2]W_0, W_{25}, W_{50}, W_{75}, W_{100} - 0, 25, 50, 75 and 100% of wheat included in the diet at 50% was replaced with WW.

It has been found that enhancing feed grinding efficiency would increase the exposure of nutrients to digestive fluids, thus improving nutrient digestion (Ferket, 2000; Ravindran *et al.*, 2006). In the experiment performed by Jankowski *et al.* (2013a), no differences were found in the digestibility coefficients of dry matter and crude fibre or the coefficients of nitrogen retention between groups. Therefore it can be concluded that although the presence of WW in the diet increased the amount of coarse particles in the digesta leaving the gizzard, neither apparent digestibility of dry matter and crude fibre nor nitrogen retention were negatively affected.

Effect of WG on caeca development and functionality

EFFECT OF WG FEEDING ON THE AMOUNT AND PROPERTIES OF THE CAECAL DIGESTA

According to Svihus *et al.* (2013), due to the anatomical and physiological adaptations of the caeca, only small and/or soluble particles can be refluxed into the caeca together with uric acid and digestive fluids. Therefore, an important question arises as to what dietary inclusion level of WG affects caecal function.

In broiler chickens, the weight of the caecal digesta increased linearly with dietary inclusion rates of WG (Wu *et al.*, 2004; Wu and Ravindran, 2004; Ravindran *et al.*, 2006; Amerah and Ravindran, 2008). Similar results were reported for turkeys fed WW along with a protein-mineral-vitamin concentrate (PC) or complete diet (CD) (Jankowski *et al.*, 2013b and Zdunczyk *et al.*, 2013, respectively). The bulk caecal digesta effect was not observed when turkeys were fed a diet supplemented with 20% WW before pelleting (Jankowski *et al.*, 2014). Interestingly, pre-pelleting inclusion of WW in turkey diets resulted in significantly higher concentrations of caecal short-chain fatty acids (SCFAs), in comparison with the control group ($P<0.001$).

Previous experiments (Gabriel *et al.*, 2003a; 2003b; 2008; Taylor and Jones, 2004; Biggs and Parsons, 2009) demonstrated that the WG content of chicken diets had no effect on SCFA concentrations in the caecal digesta. According to Gabriel *et al.* (2008), WW grains improve gizzard function and nutrient digestibility, thus reducing the amount of substrate available for the proliferation of intestinal microbiota and the amount of fermentation products in the caeca. In an experiment with turkeys, significantly higher concentrations of caecal SCFAs were noted if the CD was diluted with WW at 22.5% in

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the final phase of feeding (Zdunczyk *et al.*, 2013). In another experiment (Jankowski *et al.*, 2013b), significantly lower SCFA concentrations in the caecal digesta were noted when GW was completely replaced with WW. This is consistent with the findings of Gabriel *et al.* (2008) who reported that through improved gizzard function and nutrient digestibility, WG inclusion might also be associated with a reduced amount of substrate available for the proliferation of intestinal microflora, thus suppressing intestinal fermentation processes.

EFFECT OF WG FEEDING ON CAECAL MICROBIOTA

In poultry, the pair of caeca is located at the junction of the ileum and colon as elongated blind sacs directed along the ileum (McLelland, 1989). In turkeys, the caeca are distinctly longer than in chickens, and a highly fibrous diet increases the dry matter content of caeca (Duke *et al.*, 1984). The functionality of caeca has been found to be largely affected by fermentation-prone dietary carbohydrates such as fructans, raffinose family oligosaccharides and pectins (Juskiewicz *et al.*, 2002; 2006).

Table 3 Digestive tract microbiota of broilers and turkeys fed diets with and without WG.

Reference	Short protocol design	Main results
Gabriel *et al.* (2003b)	Chicken were fed a standard diet containing 40% GW or the same diet where part of wheat was offered separately as WG whose content was increased progressively from 20% at 8 days of age to 40% at 22 days	WG decreased the counts of ileal facultative anaerobic bacteria, but had no effect on the counts of ileal *E. coli* and *Lactobacillus*. In the jejunum and caeca, no differences in microbiota counts were observed.
Singh *et al.* (2014b)	Five diets, containing 60% of ground corn or 15, 30, 45 and 60% of whole corn (WC) replacing ground corn were formulated and cold-pelleted at 65°C	A linear ($P < 0.05$) effect was noted for caecal microbiota counts: an increase in *Lactobacillus spp.*, and a decrease in Clostridium spp., Campylobacterium spp. and *Bactroides spp.* counts with increasing inclusion levels of WC.
Zdunczyk *et al.* (2013)	CD was diluted with GW or WW, at a low and high dilution level (LW and HW, respectively), *i.e.* 5/15% and 12.5/22.5% in weeks 5-8 and 17-18, respectively	In comparison with control, higher dietary inclusion of WW increased *Bacteria* and *Bifidobacterium* counts, and decreased *Salmonella* counts in the caecal digesta
Jankowski *et al.* (2013b)	GW was replaced with increasing rates of WW at 25, 50, 75 and 100% in two feeding periods of 5 - 8 and 9 - 12 weeks	Increasing dietary inclusion levels of WW had no influence on total caecal bacterial counts, whereas a linear decrease was observed in the counts of *E. coli*, Clostridiaceae and Clostridium perfingens.

As shown in *Table 3*, the dietary inclusion of WG influenced the microbial ecology of the gastrointestinal tract of poultry, in both broilers and turkeys. In experiments involving chickens (Singh *et al.*, 2014b) and turkeys (Jankowski *et al.*, 2013b; Zdunczyk *et al.*, 2013), positive trends included a decrease in the counts of *Clostridium spp.*, *Campylobacter* and/or *Escherichia coli*, and an increase in the counts of *Lactobacillus spp.* and/or *Bifidobacterium*. In other studies of broilers, the dietary inclusion of WW has been shown to decrease intestinal *Salmonella spp.* colonisation (Bjerrum *et al.*, 2005; Santos *et al.*, 2008) and the counts of *C. perfringens* (Bjerrum *et al.*, 2005), and increase

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the counts of beneficial microbiota such as *Lactobacillus spp.* (Gabriel *et al.*, 2006). According to Singh *et al.* (2014b), WG may encourage the colonisation of commensal bacteria and discourage the growth of pathogenic and harmful bacteria in the gastrointestinal tract through competitive exclusion, hydrochloric acid secretion, the grinding action of the gizzard or a combination of all those factors.

Effect of WG feeding on intestinal morphology

The results of a few experiments performed on chickens to determine the effect of dietary inclusion of WG on intestinal morphology are ambiguous. Wu *et al.* (2004) found no effects of a diet containing 20% WW on the morphology of the gizzard and small intestine, including the thickness of the tunica muscularis layer in the gizzard or villus height, crypt depth, the number of goblet cells and epithelial thickness in the ileum. Similarly, Gabriel *et al.* (2003b) reported that the inclusion of WW in the diet did not evoke any changes at the cellular level causing no differences in cell size, tissue activity, ribosomal capacity or the rate of mitosis. In contrast, Gabriel *et al.* (2008) observed that feeding WW to chickens resulted in increased duodenal villus to crypt length and surface ratios due to lower crypt depth and a numerically smaller crypt area.

Zdunczyk *et al.* (2013) demonstrated that the physical form of wheat in turkey diets had relatively minor effects on the morphology of intestinal mucosa; an increase in the thickness of the *muscularis externa*, a decrease in crypt depth in the duodenum, and a linear decrease in villus height in the caeca were noted, but the differences were not statistically significant. In another experiment (Jankowski *et al.*, 2013b), an increase in dietary WW levels was accompanied by a tendency towards a linear increase in the thickness of muscularis externa and a decrease in crypt depth in the duodenum, and a significant linear decrease in caecal villus height.

Conclusions

Published studies investigating the effects of WG in growing turkeys are scarce, amounting to only a dozen in comparison with over 110 experiments related to chicken nutrition, whose findings have been summarised in a review article by Singh *et al.* (2014a). The results of experiments performed on turkeys indicate that, similarly to chickens, gizzard weight increases in response to an increase in feed particle size or incorporation of WG into the diet. The presence of WG in the diet leads to an increase in the amount of coarse particles in the digesta leaving the gizzard, with no negative effects on the apparent digestibility of dry matter and crude fibre or nitrogen retention values. The dietary inclusion of WG can reduce the populations of pathogenic microbiota and increase the counts of beneficial bacteria in the lower gut. Further research should be aimed at determining the dietary inclusion rate of WG required to increase gizzard weight and induce desirable changes in microbiota populations and fermentation processes in the lower GIT.

References

AMERAH, A.M., RAVINDRAN, V., LENTLE, R.G. and THOMAS, D.G. (2007) Feed particle size: Implication on the digestion and performance of poultry. *World's Poultry Science Journal* **63**: 439-453.

https://doi.org/10.1017/S0043933916000507 Published online by Cambridge University Press

AMERAH, A.M. and RAVINDRAN, V. (2008) Influence of method of whole-wheat feeding on the performance, digestive tract development and carcass traits of broiler chickens. *Animal Feed Science and Technology* **147**: 326-339.

AMERAH, A.M., RAVINDRAN, V., LENTLE, R.G. and THOMAS, D.G. (2008) Influence of feed particle size on the performance, energy utilisation, digestive tract development, and digesta parameters of broiler starters fed wheat- and corn-based diets. *Poultry Science* **87**: 2320-2328.

AMERAH, A.M., PERON, A., ZAEFARIAN, F. and RAVINDRAN, V. (2011) Influence of whole wheat inclusion and a blend of essential oils on the performance, nutrient utilisation, digestive tract development and ileal microbiota profile of broiler chickens. *British Poultry Science* **52**: 124-132.

BANFIELD, M.J. and FORBES, J.M. (2001) Effects of whole wheat dilution versus substitution on coccidiosis in broiler chickens. *British Journal of Nutrition* **86**: 89-95.

BENNETT, C.D., CLASSEN, H.L., SCHWEAN, K. and RIDDELL, C. (2002) Influence of whole barley and grit on live performance and health of turkey toms. *Poultry Science* **81**: 1850-1855.

BIGGS, P. and PARSONS., C.M. (2009) The effect of whole grains on nutrient digestibilities, growth performance, and cecal short-chain fatty acid concentrations in young chicks fed ground corn-soybean meal diets. *Poultry Science* **88**: 1893-1905.

BJERRUM, L., PEDERSEN, K. and ENGBERG, R.M. (2005) The influence of whole wheat feeding on Salmonella infection and gut flora composition in broilers. *Avian Diseases* **49**: 9-15.

CHOCT, M. (2009) Managing gut health through nutrition. *British Poultry Science* **50**: 9-15.

DUKE, G.E., ECCLESTON, E., KIRKWOOD, S., LOUIS, C.F. and BEDBURY, H.P. (1984) Cellulose digestion by domestic turkeys fed low or high fiber diets. *Journal of Nutrition* **114**: 95-102

DUKE, G.E. (1992) Recent studies on regulation of gastric motility in turkeys. *Poultry Science* **71**: 1-8

ENGBERG, R.M., HEDEMANN, M.S. STEENFELDT, S. and JENSEN, B.B. (2004) Influence of whole wheat and xylanase on broiler performance and microflora composition and activity of the digestive tract. *Poultry Science* **83**: 925-938.

FAVERO, A., MAIORKA, A., FISCHER DA SILVA, A.V., DE PAULA VALLE, F.B., DOS SANTOS, S. A. and MURAMATSU K. (2012) Influence of feed form and corn particles size on nutrient digestibility and energy utilisation by young turkeys. *Revista Brasileira de Zootecnia* 41: 86-90.

FERKET, P. (2000) Feeding whole grains to poultry improves gut health. *Feedstuffs* **72**: 12-16.

FRANCESCH, M. and BRUFAU, J. (2004) Nutritional factors affecting excreta/litter moisture and quality. *World's Poultry Science Journal* **60**: 64- 75.

GABRIEL, I., MALLET, S., LECONTE, M., FORT, G. and NACIRI, M. (2003a) Effects of whole wheat feeding on the development of coccidial infection in broiler chickens. *Poultry Science* **82**: 1668-1676.

GABRIEL, I., MALLET, S. and LECONTE, M. (2003b) Differences in the digestive tract characteristics of broiler chickens fed on complete pelleted diet or on whole wheat added to pelleted protein concentrate. *British Poultry Science* **44**: 283-290.

GABRIEL, I., MALLET, S., LECONTE, M., FORT, G. and NACIRI, M. (2006) Effects of whole wheat feeding on the development of coccidial infection in broiler chickens until market-age. *Animal Feed Science and Technology* **129**: 279-303.

GABRIEL, I., MALLET, S., LECONTE, M., TRAVEL, A. and LALLES, J.P. (2008) Effect of whole wheat feeding on the digestive tract of broiler chickens. *Animal Feed Science and Technology* **142**: 144-162.

GJEVRE, A.G., KALDHUSDAL, M. and ERIKSON, G.S. (2013) Gizzard erosion and ulceration syndrome in chickens and turkeys: a review of casual or predisposing factors. *Avian Pathology* **42**: 297-303.

HETLAND, H., SVIHUS, B. and OLAISEN, V. (2002) Effect of feeding whole cereals on performance, starch digestibility and duodenal particle size distribution in broiler chickens. *British Poultry Science* **43**: 416-423.

HETLAND, H., SVIHUS, B. and KROGDAHL, A. (2003) Effects of oat hulls and wood shavings on digestion in broilers and layers fed diets based on whole or ground wheat. *British Poultry Science* **44:** 275-282.

JACKSON, S. and DUKE, G.E. (1995) Intestine fullness influences feeding behaviour and crop filling in the domestic turkey. *Physiology and Behavior* **58**: 1027-1034.

JANKOWSKI, J., MIKULSKI, D., ZDUNCZYK, Z. and JUSKIEWICZ, J. (2013a) A note on the particle size distribution of intestinal digesta and nutrient digestibility in growing turkeys fed diets with different whole-grain wheat contents. *Journal of Animal and Feed Sciences* **22**: 364-368.

JANKOWSKI, J., ZDUNCZYK, Z., MIKULSKI, D., PRZYBYLSKA-GORNOWICZ, B., SOSNOWSKA, E. and JUSKIEWICZ, J. (2013b) Effect of whole wheat feeding on gastrointestinal tract development and performance of growing turkeys. *Animal Feed Science and Technology* **185**: 150-159.

JANKOWSKI, J., MIKULSKI, D., ZDUNCZYK, Z., JUSKIEWICZ, J. and LICHTOROWICZ, K. (2014) Gastrointestinal tract response and growth performance of growing turkeys as influenced by the whole wheat content of diets in two feeding programmes. *Journal of Animal and Feed Sciences* **23**: 253-261.

JUSKIEWICZ, J., ZDUNCZYK, Z., JANKOWSKI, J. and KROL, B. (2002) Caecal metabolism in young turkeys fed diets supplemented with oligosaccharides. *European Poultry Science* **66**: 206-210.

https://doi.org/10.1017/S0043933916000507 Published online by Cambridge University Press

JUSKIEWICZ, J., JANKOWSKI, J., ZDUNCZYK, Z. and MIKULSKI, D. (2006) Performance and gastrointestinal tract metabolic of turkeys fed diets with different content of fructooligosaccharide. *Poultry Science* **85**: 886-891.

KALDHUSDAL, M., HETLAND, H. and GJEVRE, A.G. (2012) Non-soluble fibres and narasin reduce spontaneous gizzard erosion and ulceration in broiler chickens. *Avian Pathology* **41**: 227-234.

KONCA, Y., KIRKPINAR, F., MERT, S. and ATAC, C. (2012) Effects of mixed or separate feeding with whole barley or triticale on growth performance, gastrointestinal system, nutrient digestibility and blood constituents in turkeys. *Revue De Medecine Veterinaire* **163**: 522-529.

LENTLE, R.G., RAVINDRAN, V., RAVINDRAN, G. and THOMAS, D.V. (2006) Influence of feed particle size on the efficiency of broiler chickens fed wheat-based diet. *Journal of Poultry Science* **43**: 135-142.

MAYNE, R.K., ELSE, R.W. and HOCKING, P.M. (2007) High litter moisture alone is sufficient to cause footpad dermatitis in growing turkeys. *British Poultry Science* **48**: 538-545.

MCLELLAND, J. (1989) Anatomy of the avian cecum. *Journal of Experimental Zoology* **3**: 2-9.

NRC (1994) Nutrient Requirements of poultry. 9th revised Edition. *National Academic Press* Washington, DC.

PALANDER, S., NÄSI, M. and JÄRVINEN, S. (2005) Effect of age of growing turkeys on digesta viscosity and nutrient digestibility of maize, wheat, barley and oats fed as such or with enzyme. supplementation. *Archives of Animal Nutrition* **59**: 191-203.

PLAVNIK, I., MACOVSKY, D. and SKLAN, D. (2002) Effect of feeding whole wheat on performance of broiler chickens. *Animal Feed Science and Technology* **96**: 229-236.

RAVINDRAN, V., WU, Y.B., THOMAS, D.G. and MOREL, P.C.H. (2006) Influence of whole wheat feeding on the development of gastrointestinal tract and performance of broiler chickens. *Australian Journal of Agricultural Research* **57**: 21-26.

ROCHE, M. (1981) Feeding behaviour and digestive motility of birds. *Reproduction Nutrition Development* **21**: 781-788.

SANTOS, F.B.O., SHELDON, B.W., SANTOS, A.A. and FERKET P.R. (2008) Influence of housing system, grain type, and particle size on *Salmonella* colonisation and shedding of broilers fed triticale or corn-soybean meal diets. *Poultry Science* **87**: 405-420.

SERRANO, M.O., FRIKHA, M., CORCHERO, J. and MATEOS, G.G. (2013) Influence of feed form and source of soybean meal on growth performance, nutrient retention, and digestive organ size of broilers. 2. Battery study. *Poultry Science* **92**: 693-708.

SINGH, Y., AMERAH, A.M. and RAVINDRAN, V. (2014a) Whole grain feeding: Methodologies and effects on performance, digestive tract development and nutrient utilisation of poultry. *Animal Feed Science and Technology* **190**: 1-18.

SINGH, Y., RAVINDRAN, V., WESTER, T.J., MOLAN, A.L. and RAVINDRAN, G. (2014b) Influence of prepelleting inclusion of whole corn on performance, nutrient utilisation, digestive tract measurements, and caecal microbiota of young broilers. *Poultry Science* **93**: 3073-3082.

SVIHUS, B., HERSTAD, O., NEWMAN, C.W. and NEWMAN, R.K. (1997) Comparison of performance and intestinal characteristics of broiler chickens fed on diets containing whole, rolled or ground barley. *British Poultry Science* **38**: 524-529.

SVIHUS, B., HETLAND, H., CHOCT, M. and SUNDBY, F. (2002) Passage rate through the anterior digestive tract of broiler chickens fed on diets with ground or whole wheat. *British Poultry Science* **43**: 662-668.

SVIHUS, B. (2011) The gizzard: function, influence of diet structure and effects on nutrient availability. *World's Poultry Science Journal* **67**: 207-224.

SVIHUS, B., CHOCT, M. and CLASSEN, H.L. (2013) Function and nutritional roles of the avian caeca: A review. *World's Poultry Science Journal* **69**: 249-263.

SVIHUS, B. (2014) Function od digestive system. *Journal of Applied Poultry Research* **23**: 306-314.

TAYLOR, R.D. and JONES, G.P.D. (2004) The incorporation of whole grain into pelleted broiler chicken diets. II. Gastrointestinal and digesta characteristics. *British Poultry Science* **45**: 237-246.

WU, Y.B. and RAVINDRAN, V. (2004) Influence of whole wheat inclusion and xylanase supplementation on the performance, digestive tract measurements and carcass characteristics of broiler chickens. *Animal Feed Science and Technology* **116**: 129-139.

WU, Y.B., RAVINDRAN, V., THOMAS, D.G., BIRTLES, M.J. and HENDRIKS, W.H. (2004) Influence of method whole wheat inclusion and xylanase supplementation on the performance, apparent metabolisable energy, digestive tract measurements and gut morphology of broiler. *British Poultry Science* **45**: 385-394.

ZDUNCZYK, Z., JANKOWSKI, J., MIKULSKI, D., PRZYBYLSKA-GORNOWICZ, B., SOSNOWSKA, E. and JUSKIEWICZ, J. (2013) Gastrointestinal morphology and function in turkeys fed diet diluted with whole grain wheat. *Poultry Science* **92**: 1799-1811.

XU, Y., STARK, R., FEREKT, P.R., WILLIAMS, C.M. and BRAKE, J. (2015) Effect 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. *Poultry Science* **94**: 1549-1556.

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