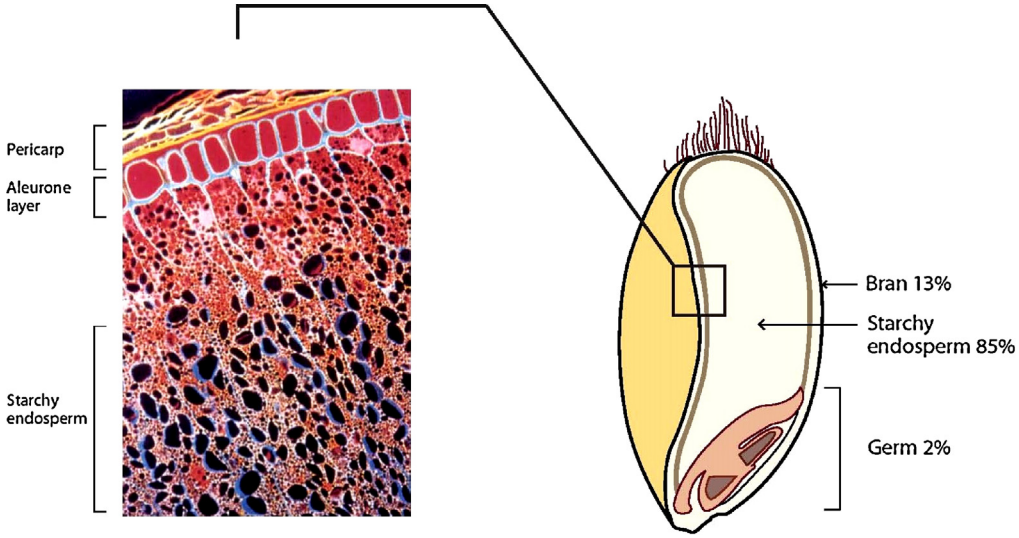

Fig. 1. Wheat kernel.

et al., 2006). Interestingly, there is little information available on the effect of these inhibitors on exogenous xylanase supplementation.

3. Wheat physical structure

A mature, wheat kernel is divided into three basic units, 13% bran layer, 2% embryo and 85% endosperm (Fig. 1). The bran layer is comprised of the high NSP content pericarp and the aleurone layer, which is made up of equal amounts of oil, mineral matter and protein (Ravindran and Amerah, 2009). The endosperm consists mainly of starch granules that are surrounded by a protein matrix. As the bulk of the wheat kernel is the endosperm, the physical quality of this part is of greatest importance. Hardness of the endosperm is one of the important characteristics of wheat grain that determines the particle size and end use of the wheat flour. The relative hardness or softness of a grain has been defined as the relative resistance of grains to deformation or crushing when an external force is applied (Turnbull and Rahman, 2002). It is not the aim of this paper to review factors determining wheat hardness as this subject was recently reviewed by Pasha et al. (2010). Briefly, hardness is a genetic trait determined by the Hardness (Ha) locus on chromosome 5D that encodes for the puroindolines a and b, also called friabilin or grain softness protein (Sourdille et al., 1996). Endosperm hardness is also influenced by other factors, such as environmental conditions (Stenvert and Kingswood, 1977; Dobraszczyk et al., 2002) protein content (Cornell and Hoveling, 1998; Turnbull et al., 2002) quantity and quality of pentosans and moisture content (Turnbull and Rahman, 2002).

Studies on the effect of wheat endosperm hardness on broiler performance are limited. The effect of wheat hardness on broiler performance appears to be influenced by the feed form. Harder wheat produces larger particle size flours, which may account for the better broiler performance reported using mash diets based on hard wheats (Rose et al., 2001; Pirgozliev et al., 2003; Amerah et al., 2007). In contrast, in pelleted diets, no effect of wheat hardness was found on broiler performance (Salah Uddin et al., 1996). Similarly, Hetland et al. (2007) found no relationship between wheat hardness and broiler performance in pelleted diets. In some cases, pelleting may even out differences in particle size distribution (Svihus et al., 2004) and reduce the effect of wheat hardness on performance.

Other measurements of physical quality of wheats include, thousand grain weight and bushel weight. However, research results in general showed inconsistent and poor correlations of these characteristics with broiler performance. Miller et al. (2001) in an extensive study examined the effect of 16 wheat samples in feeding experiments. They reported an increase in starch concentration and a trend for crude protein reduction with increasing specific weight of wheat, whilst modified acid detergent fibre decreased indicating a shift in the composition of the complex carbohydrate fraction of the grain with changing specific weight. However, despite these changes in the chemical composition with different specific weights of wheat this was not reflected in broiler performance (Miller et al., 2001). Home Grown Cereals Authority (HGCA, 2001) found no consistent effect of specific weight on chicken performance. Hruby (unpublished data) showed a poor correlation of specific weight with wheat AME (Fig. 2). McCracken et al. (2002) reported also a weak (R^2 = 0.18) positive relationship between ME:GE and specific weight corresponding to a 2.5% increase in energy value for every 10 kg/hl increase. However, when one wheat variety was removed, the regression the slope was similar but R^2 increased to 0.82. This effect also was not reflected in performance. They concluded that if the variety is known, then specific weight could be used to predict energy value. In contrast, Svihus and Gullord (2002) reported a positive (R^2 = 0.46) relationship between specific weight and weight gain without enzyme supplementation and no significant correlation was found between wheat specific weight and the metabolisable energy. The same researchers found no correlation between thousand grain weight and metabolisable energy

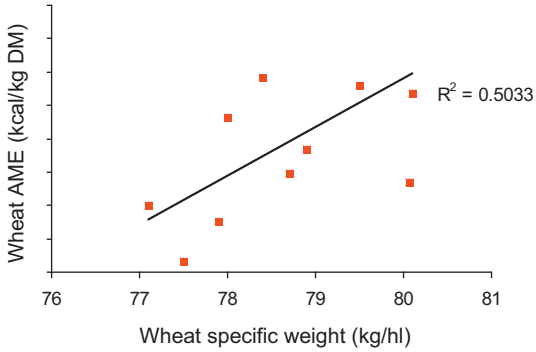

Fig. 2. Correlation between wheat specific weight and the apparent metabolisable energy of wheat (M. Hruby, unpublished data).

or broiler performance. More recently, Ball et al. (2013) reported no correlation between specific weights of wheat and broiler performance, but thousand grain weight was positively correlated with dry matter intake (R^2 = 0.299), weight gain (R^2 = 0.343) and gain to feed (R^2 = 0.371). Sibbald and Price (1976) established that the relationship between the same two physical terms and either AME or metabolizability of gross energy was not significant. The correlation coefficient between grain weight and ME reported by March and Biely (1973) was only −0.004. Wiseman (2000) concluded that there does not appear to be any relationship between two commonly derived physical measurements, specific weight and thousand grain weight, and dietary energy value of wheat for young poultry and for pigs.

Another wheat quality measurement is Hagberg falling number (HFN). In this measurement, whole wheat flour is mixed with water and gelatinised by heating. A plunger is then allowed to fall under the force of gravity through the mixture, and the time (in s) it takes for a plunger to fall a certain distance is recorded. High α-amylase activity due to pre-harvest sprouting, causes liquefaction of the starch, and therefore lowers the HFN. The reported effects of HFN on broiler performance and nutrient digestibility are inconsistent. Pirgozliev et al. (2003) reported no correlation between HFN and broiler performance and AME. In contrast, Svihus and Gullord (2002) reported a negative correlation between HFN and AME. Rose et al. (2001) found that feed conversion ratio decreased with increasing HFN. More recently, Hetland et al. (2007) reported inconsistent effect of HFN on nutrient digestion and broiler performance.

4. Wheat quality and enzyme supplementation

The application of endo-1,4-beta-xylanase and phytase enzymes to poultry diets based on wheat is well accepted. Xylanase degrades arabinoxylans in the cell wall, releasing encapsulated starch and other nutrients from inside the cell wall, at the same time as reducing digesta viscosity caused by the soluble fraction. The net effects are improvement in performance and nutrient digestibility, reduction in the incidence of sticky droppings and modification the microflora of the distal gut (Cowieson et al., 2006). Broiler performance variation due to variation in chemical and/or physical structure of the wheat was suggested to be reduced by xylanase supplementation (Bedford, 2000). Broiler responses to xylanase supplementation, however, have not been consistent and differences between different wheat cultivars still existed (Gutierrez del Alamo et al., 2008). Factors that may cause variation in response include the type of xylanase, quality of the wheat and breed and age of the birds (Bedford, 1997). Some studies have shown that differences in the response of enzyme supplementation might be related to hindgut microflora (Choct et al., 1996; Choct et al., 2006). Other factors suggested to explain variation between individual birds within the same treatment group include diurnal rhythms, water intake patterns and pancreatic serous secretion output (Bedford and Schulze, 1998).

Phytase is another enzyme widely used in either corn or wheat based diets. This enzyme cleaves phosphate groups from phytate, thus increasing phosphorus (P) availability and mitigating the anti-nutritional effect of phytate. As discussed earlier, the level of phytate varies considerably between the different wheat cultivars (Selle et al., 2003). Afsharmanesh et al. (2008) reported different response to phytase according to wheat cultivar and grind size. They suggested that in HRS wheat larger particles resulted in higher phytase efficiency in the gizzard at low pH.

High variability in wheat arabinoxylan level is known to influence its nutritive value and consequently the effect on performance (Annison, 1991; Choct et al., 1995, 1999). The higher the NSP level, the higher xylanase response is to be expected. This is well documented and has been discussed previously by several authors (Bedford and Schulze, 1998; Bedford, 1997, 2000, 2006). However, a recent study showed that the ratio of arabinose to xylose can predict the xylanase responses and that a higher ratio showed less susceptibility to degradation by xylanase (Smeets et al., 2014).

Studies examining the effect of endogenous xylanase inhibitor in wheat on broiler performance and nutrient digestibility are limited. Wheat varieties vary in their inhibitory effect with most of the inhibition being found in the endosperm (Rouau and Surget, 1998; Bonnin et al., 2005). Verhoeven et al. (2005) suggested that there is approximately 250 times more inhibitor present in wheat than the amount of xylanase added, but lack of contact between the two compounds ameliorate the effect of inhibitors in birds. In contrast, it has been suggested that these xylanase inhibitors can modulate broilers response to

Table 2
Influence of wheat hardness and xylanase supplementation on weight gain (g/bird), feed intake (g/bird), feed per gain (g/g) and AMEn (MJ/kg dry matter) for broilers (1–21 days posthatch)[a].

	Wheat hardness enzyme	Weight gain	Feed intake	Feed per gain	AMEn
Soft wheat	–	912[b]	1261[c]	1.389[a]	13.59[a]
	+	958[c]	1338[a]	1.397[a]	13.45[a]
Hard wheat	–	991[a]	1401[b]	1.414[a]	13.51[a]
	+	977[a]	1319[a]	1.351[b]	13.84[b]
SEM[b]		12	16	0.013	0.08
Probabilities, P≤					
Xylanase		NS	NS	*	NS
Wheat hardness		***	***	NS	0.08
Xylanase × Wheat hardness		*	**	*	**

NS, not significant. [a,b]Means in a column not sharing a common superscript are significantly different (P<0.05).
* P<0.05.
** P<0.01.
*** P<0.001.
[a] Adapted from Amerah et al. (2009).
[b] Pooled standard error of mean.

exogenous xylanases (Ponte et al., 2004). However, in reality, the effect of these inhibitors has not been demonstrated *in vivo* considering the number of reports showing the positive effect of xylanase using different wheat cultivars and both in mash or pelleted diets. Whether these inhibitors are thermostable under commercial feed processing is also not clear (Ponte et al., 2004; Verhoeven et al., 2005). It is noteworthy that the ability of the xylanase to resist inhibition is one of the criteria when developing a new commercial xylanase molecule.

Research data which relate physical quality, enzyme supplementation and nutrient digestibility are limited. It has been suggested that the higher amount of damaged starch in hard wheat makes starch easily hydrolysed by α- amylase (Tester and Karkalas, 2004). This is related to a higher capacity of the damaged starch to absorb water and consequently increased susceptibility to amylolysis (Kent and Evers, 1996). In contrast, Wiseman (2006) stated that soft wheats may have better hydration patterns and therefore better starch digestibility. This effect might be related to the degree and type of grinding, feed form and heat treatment of the diet. A negative relationship between wheat hardness and the digestibility of starch in pelleted diets has been reported (Carre et al., 2002, 2005; Peron et al., 2006; Ball et al., 2013). The theory behind this finding was attributed to larger particulate size reducing the surface area and accessibility for digestive enzymes (Carre et al., 2005). In support of this theory, Peron et al. (2005) found that fine grinding of hard wheat improved starch digestibility in broilers fed pelleted diets. Similarly, Short et al. (2000) found that the hard wheat endosperm was associated with lower amino acid digestibility. It has been suggested that the interaction between the starch granules and the surrounding protein matrix may act to obstruct enzyme hydrolysis of starch in hard wheat (Guerrieri et al., 1997; Peron et al., 2006). Therefore, protease supplementation may have a beneficial effect on starch digestibility by improving the accessibility of amylolytic enzymes to starch granules in the endosperm by hydrolysing the surrounding protein matrix. A commercial combination of xylanase and protease has been found to improve performance of wheat-based feeds in both poultry and pigs (Bedford et al., 1997). In an *in vitro* study, Zyla et al. (1999) reported that over the entire range of phytase concentrations studied (250, 500, 750 and 1000 FTU/kg) no significant effect of xylanase addition on phosphorus release was found, whereas protease addition effect was significant. Interestingly, these researchers also reported that both phytase and protease resulted in increases in amounts of pentose sugars freed from feeds. However, the exact mechanism is not clear. Amerah et al. (2009) reported interactions between wheat hardness and xylanase supplementation for weight gain, feed intake, feed per gain and nitrogen corrected apparent metabolisable energy (AMEn; Table 2). Enzyme supplementation increased weight gain in the soft wheat-based diet but not in the hard wheat diet. Enzyme supplementation also increased feed intake in the soft wheat-based diet, but reduced intake in the hard wheat diet. Feed per gain and AMEn were improved by enzyme supplementation in the hard wheat-based diet, while no enzyme effect was observed in the soft wheat diet They suggested that the beneficial effect of xylanase supplementation in the hard wheat-based diet may be related to greater grinding activity and mixing in the gizzard as indicated by the higher relative weight of gizzard digesta content. A higher proportion of fine particles were also observed in the proximal intestinal digesta in birds fed hard wheat-based diets further supporting the thesis that gizzard function was improved on hard wheat diets. The other possibility is that the cell walls of coarser particles of the hard wheat-based diet are less disrupted and this may explain the greater efficacy of cell wall degrading enzymes in coarse or whole wheat diets. Surprisingly, the improvement in feed per gain with whole wheat feeding was concurrent with increased digesta viscosity (Engberg et al., 2004; Wu et al., 2004). These results suggested that reduction in digesta viscosity is not the only mechanism associated with enzyme supplementation. Further studies are required to fully understand the factors that may affect broiler performance, nutrient utilisation and enzyme supplementation in relation to wheat hardness.

In one trial, McCracken and Quintin (2000) reported a significant wheat specific weight × enzyme combination interaction for feed to gain with no improvement due to enzyme addition for higher specific weight wheat compared to lower specific weight wheat. However, this interaction effect can be due to other wheat qualities that were not studied in this trial.

The physical form of the diet (mash, pellet and whole grains), other dietary ingredients and processing methods may also affect the efficacy of exogenous enzymes in poultry diets (Amerah et al., 2011). The beneficial effects of including whole wheat were shown to be further enhanced with supplemental xylanase (Wu and Ravindran, 2004). This additive effect was attributed to higher grinding activity of the larger gizzard in birds fed whole grains leading to enhanced mixing of the substrate with the supplemental enzyme in the gizzard. Amerah et al. (2008) reported a significant particle size × xylanase interaction for feed to gain with xylanase improving feed to gain only in the coarse particle size diet.

In conclusion, hardness appears to be the most important physical quality of wheat that influences both broiler performance and response to exogenous enzymes. This effect of wheat hardness may be related to particle size distribution of the ground wheat which may influence residence time of digesta in the gut (primarily gizzard) and the time of exposure to exogenous enzymes. On the other hand, a negative relationship between wheat hardness and the digestibility of starch in pelleted diets has been reported. For the chemical characteristics, the level and structure of the NSP are important criteria in determining the feeding quality of the wheat and the enzyme response. Further studies are required to better understand the effect of physical qualities of wheat and how they influence the response to feed enzymes.

Conflict of interest

None.

References

Adeola, O., Cowieson, A.J., 2011. Opportunities and challenges in using enzymes to improve nonruminant animal production. J. Anim. Sci. 89, 3189–3218.

Afsharmanesh, M., Scott, T.A., Silversides, F.G., 2008. Effect of wheat type, grinding, heat treatment, and phytase supplementation on growth efficiency and nutrient utilization of wheat-based diets for broilers. Can. J. Anim. Sci. 88, 57–64.

Amerah, A.M., Ravindran, V., Lentle, R.G., Thomas, D.G., 2007. Feed particle size: implications on the digestion and performance of poultry. World's Poult. Sci. J. 63, 439–455.

Amerah, A.M., Ravindran, V., Lentle, R.G., Thomas, D.G., 2008. Influence of particle size and xylanase supplementation on the performance, energy utilisation, digestive tract parameters and digesta viscosity of broiler starters. Br. Poult. Sci. 49, 455–462.

Amerah, A.M., Ravindran, V., Lentle, R.G., 2009. Influence of wheat hardness and xylanase supplementation on the performance, energy utilisation, digestive tract development and digesta parameters of broiler starters. Anim. Prod. Sci. 49, 71–78.

Amerah, A.M., Gilbert, C., Simmins, P.H., Ravindran, V., 2011. Influence of feed processing on the efficacy of exogenous enzymes in broiler diets. World's Poult. Sci. J. 67, 29–46.

Annison, G., 1991. Relationship between the levels of soluble nonstarch polysaccharides and apparent metabolizable energy of wheats assayed in broiler chickens. J. Agric. Food Chem. 39, 1252–1256.

Ball, M.E.E., Owens, B., McCracken, K.J., 2013. Chemical and physical predictors of the nutritive value of wheat in broiler diets. Asian-Aust. J. Anim. Sci. 26, 97–107.

Barrier-Guillot, B., Casado, P., Maupetit, P., Jondreville, C., Gatel, F., 1996a. Wheat phosphorus availability: 1-in vitro study; factors affecting endogenous phytasic activity and phytic phosphorus content. J. Sci. Food Agric. 70, 62–68.

Barrier-Guillot, B., Casado, P., Maupetit, P., Jondreville, C., Gatel, F., 1996b. Wheat phosphorus availability: 2-in vivo study in broilers and pigs; relationship with endogenous phytasic activity and phytic phosphorus content in wheat. J. Sci. Food Agric. 70, 69–74.

Bedford, M.R., 1996. The effect of enzymes on digestion. J. Appl. Poult. Res. 5, 370–378.

Bedford, M.R., 1997. Reduced viscosity of intestinal digesta and enhanced nutrient digestibility in chickens given exogenous enzymes. In: Marquardt, R.R., Han, Z. (Eds.), Enzyme in Poultry and Swine Nutrition. International Development Research Centre, Ottawa, Canada, pp. 19–28.

Bedford, M.R., Morgan, A.J., Clarkson, K., Schultze, H.K., 1997. Enzyme feed additive and animal feed. US Patent 5612055.

Bedford, M.R., 2000. Exogenous enzymes in monogastric nutrition: their current value and future benefits. Anim. Feed Sci. Technol. 86, 1–13.

Bedford, M.R., 2006. Effect of non-starch polysaccharides on avian gastrointestinal function. In: Perry, G.C. (Ed.), Avian gut function in health and disease. CAB International, Wallingford, UK, pp. 159–170.

Bedford, M.R., Schulze, H., 1998. Exogenous enzymes for pigs and poultry. Nutr. Res. Rev. 11, 91–114.

Bonnin, E., Daviet, S., Gebruers, K., Delcour, J.A., Goldson, A., Juge, N., Saulnier, L., 2005. Variation in the levels of the different xylanase inhibitors in grain and flour of 20 French wheat cultivars. J. Cereal Sci. 41, 375–379.

Bonnin, E., Le Goff, A., Saulnier, L., Chauraud, M., Thibault, J.-F., 1998. Preliminary characterisation of endogenous wheat arabinoxylandegrading enzymic extracts. J. Cereal Sci. 28, 53–62.

Carre, B., Maisonnier Melcion, J.P., Ouryt, F.X., Gomez, J., Pluchard, P., 2002. Relationships between digestibilities of food components and characteristics of wheats (*Triticum aestivum*) introduced as the only cereal source in a broiler chicken diet. Br. Poult. Sci. 43, 404–415.

Carre, B., Muley, N., Gomez, J., Ouryt, F.X., Laffitte, E., Guillou, D., Signoret, C., 2005. Soft wheat instead of hard wheat in pelleted diets results in high starch digestibility in broiler chickens. Br. Poult. Sci. 46, 66–74.

Carre, B., Mignon-Grasteau, S., Peron, A., Juin, A.H., Bastianelli, D., 2007. Wheat value: improvements by feed technology, plant breeding and animal genetics. World's Poult. Sci. J. 63, 585–596.

Choct, M., Annison, G., 1992. Antinutritive activity of wheat arabinoxylans: role of viscosity and gut microflora. Br. Poult. Sci. 33, 821–834.

Choct, M., Hughes, R.J., Trimble, R.P., Angkanaporn, K., Annison, G., 1995. Non-starch polysaccharide-degrading enzymes increase the performance of broiler chickens fed wheat of low apparent metabolizable energy. J. Nutr. 125, 485–492.

Choct, M., Hughes, R.J., Wang, J., Bedford, M.R., Morgan, A.J., Annison, G., 1996. Increased small intestinal fermentation is partly responsible for the anti-nutritive activity of non-starch polysaccharides in chickens. Br. Poult. Sci. 37, 609–621.

Choct, M., 1997. Feed Non-starch Polysaccharides: Chemical Structures and Nutritional Significance. Feed Milling International, June Issue, pp. 13–26.

Choct, M., 2006. Enzymes for the feed industry: past, present and future. World's Poult. Sci. J. 62, 5–15.

Choct, M., Hughes, R.J., Annison, G., 1999. Apparent metabolisable energy and chemical composition of Australian wheat in relation to environmental factors. Aust. J. Agric. Res. 50, 447–452.

Choct, M., Sinlae, M., Al-Jassim, R.A.M., Pettersson, D., 2006. Effects of xylanase supplementation on between-bird variation in energy metabolism and the number of Clostridium perfringens in broilers fed a wheat-based diet. Aust. J. Agric. Res. 57, 1017–1021.

Cleemput, G., Bleukx, W., van Oort, M., Hessing, M., Delcour, J.A., 1995. Evidence for the presence of arabinoxylan-hydrolysing enzymes in European wheat flours. J. Cereal Sci. 22, 139–145.

Cornell, H.J., Hoveling, A.W., 1998. Wheat Chemistry and Utilisation. Technomic, Lancaster, PA, USA, pp. 8.

Cowieson, A.J., Hruby, M., Pierson, E.E.M., 2006. Evolving enzyme technology: impact on commercial poultry nutrition. Nutr. Res. Rev. 19, 90–103.

Dobraszczyk, B.J., Whitworth, M.B., Vincent, J.F.V., Khan, A.A., 2002. Single kernel wheat hardness and fracture properties in relation to density and the modelling of fracture in wheat endosperm. J. Cereal Sci. 35, 245–263.
Dornez, E., Joye, I.J., Gebruers, K., Lenartz, J., Massaux, C., Bodson, B., Delcour, J.A., Courtin, C.M., 2006. Insight into variability of apparent endoxylanase and endoxylanase inhibitor levels in wheat kernels. J. Sci. Food Agric. 86, 1610–1617.
Engberg, R.M., Hedemann, M.S., Steenfeldt, S., Jensen, B.B., 2004. Influence of whole wheat and xylanase on broiler performance and microbial composition and activity in the digestive tract. Poult. Sci. 83, 925–938.
Gutierrez del Alamo, A., Verstegen, M.W.A., Den Hartog, L.A., Perez de Ayala, P., Villamide, M.J., 2008. Effect of wheat cultivar and enzyme addition to broiler chicken diets on nutrient digestibility, performance, and apparent metabolizable energy content. Poult. Sci. 87, 759–767.
Guerrieri, N., Aynard, L., Lavelli, V., Cerletti, P., 1997. Interaction of protein and starch studies through Amyloglucosidase action. Cereal Chem. 74, 846–850.
Gys, W., Courtin, C.M., Delcour, J.A., 2004. Debranning of wheat prior to milling reduces xylanase but not xylanase inhibitor activities in wholemeal and flour. J. Cereal Sci. 39, 363–369.
Hetland, H., Uhlen, A.K., Viken, K.H.K., Krekling, T., Svihus, B., 2007. Hagberg falling number and the nutritional value of wheat in broiler chicken diets. Br. Poult. Sci. 48, 12–20.
HGCA, 2001. Home Grown Cereals Authority Topic Sheet No. 52.
Hughes, R.J., Choct, M., 1999. Chemical and physical characteristics of grains related to variability in energy and amino acid availability in poultry. Aust. J. Agric. Res. 50, 689–701.
Kent, N.L., Evers, A.D., 1996. Kent's Technology of Cereals. Elsevier Science Ltd, Oxford, UK, pp. 62.
Kim, J.C., Simmins, P.H., Mullan, B.P., Pluske, J.R., 2005. The effect of wheat phosphorus content and supplemental enzymes on digestibility and growth performance of weaner pigs. Anim. Feed Sci. Technol. 118, 139–152.
Knudsen, B.K.E., 1997. Carbohydrate and lignin contents of plant materials used in animal feeding. Anim. Feed Sci. Technol. 67, 319–338.
Lasztity, R., 1999. Cereal Chemistry. Akademiai Kiado, Budapest.
March, B.E., Biely, J., 1973. Chemical, physical and nutritional characteristics of different samples of wheat. Can. J. Anim. Sci. 53, 569–577.
Mares, D.J., Stone, B.A., 1973a. Studies on wheat endosperm. I. Chemical composition and ultrastructure of the cell walls. Aust. J. Biol. Sci. 26, 793–812.
Mares, D.J., Stone, B.A., 1973b. Studies on wheat endosperm. II. Properties of the cell wall components and studies on their organization in the wall. Aust. J. Biol. Sci. 26, 813–830.
McCracken, K.J., Quintin, G., 2000. Metabolisable energy content of diets and broiler performance as affected by wheat specific weight and enzyme supplementation. Br. Poult. Sci. 41, 332–342.
McCracken, K.J., Preston, C.M., Butler, C., 2002. Effects of wheat variety and specific weight on dietary apparent metabolizable energy concentration and performance of broiler chicks. Br. Poult. Sci. 43, 253–260.
Miller, H.M., Wilkinson, J.M., McCracken, K.J., Knox, A., McNab, J., Rose, C.P., 2001. Nutritional value to farm livestock of wheat of low specific weight. HGCA Project Report No. 260. HGCA, London.
Pasha, I., Anjum, F.M., Morris, C.F., 2010. Grain hardness: a major determinant of wheat quality. Food Sci. Technol. Int. 16, 511–522.
Selle, P.H., Walker, A.R., Bryden, W.L., 2003. Total and phytate-phosphorus contents and phytase activity of Australian sourced feed ingredients for pigs and poultry. Aust. J. Exp. Agric. 45, 475–479.
Peron, A., Bastianelli, D., Oury, F.X., Gomez, J., Carre, B., 2005. Effects of food deprivation and particle size of ground wheat on digestibility of food components in broilers fed on a pelleted diet. Br. Poult. Sci. 46, 223–230.
Peron, A., Gomez, J., Mignon-Grasteau, S., Sellier, N., Besnard, J., Derouet, M., Juin, H., Carré, B., 2006. Effects of wheat quality on digestion differ between the D+ and D− chicken lines selected for divergent digestion capacity. Poult. Sci. 85, 462–469.
Pirgozliev, V.R., Birch, C.L., Rose, S.P., Kettlewell, P.S., Bedford, M.R., 2003. Chemical composition and the nutritive quality of different wheat cultivars for broiler chickens. Br. Poult. Sci. 44, 464–475.
Ponte, P.I.P., Ferreira, L.M.A., Soares, M.A.C., Gama, L.T., Fontes, C.M.G.A., 2004. Xylanase inhibitors affect the action of exogenous enzymes used to supplement *Triticum durum*-based diets for broiler chicks. J. Appl. Poult. Res. 13, 660–666.
Rouau, X., Surget, A., 1998. Evidence for the presence of a pentosanase inhibitor in wheatflours. J. Cereal Sci. 28, 63–70.
Ravindran, V.R., Amerah, A.M., 2009. Wheat: composition and feeding value for poultry. In: Davies, S., Evans, G. (Eds.), Soybean and Wheat Crops: Growth, Fertilization and Yield. Nova Science Publishers, United States, pp. 245–259.
Ravindran, V., Hew, L.I., Ravindran, G., Bryden, W.L., 2005. Apparent ileal digestibility of amino acids in feed ingredients for broiler chickens. Anim. Sci. 81, 85–97.
Rose, S.P., Tucker, L.A., Kettlewell, P.S., Collier, J.D.A., 2001. Rapid tests of wheat nutritive value for growing chickens. J. Cereal Sci. 34, 181–190.
Salah 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.
Scott, T.A., Silversides, F.G., Zijlstra, R.T., 2003. Effect of pelleting and enzyme supplementation on variation in feed value of wheat-based diets fed to broiler chicks. Can. J. Anim. Sci. 83, 257–263.
Selle, P.H., Ravindran, V., 2007. Microbial phytase in poultry nutrition. Anim. Feed Sci. Technol. 135, 1–41.
Short, F.J., Wiseman, J., Boorman, K.N., 2000. The effect of the 1B/1R translocation and endosperm texture on amino acid digestibility in near-isogenic lines of wheat for broilers. J. Agric. Sci. 134, 69–76.
Sibbald, I.R., Price, K., 1976. Relationships between metabolizable energy values for poultry and some physical and chemical data describing Canadian wheats, oats and barleys. Can. J. Anim. Sci. 56, 255–268.
Silversides, F.G., Bedford, M.R., 1999. Effect of pelleting temperature on the recovery and efficacy of a xylanase enzyme in wheat-based diets. Poult. Sci. 78, 1184–1190.
Slominski, B.A., Davie, T., Nyachoti, M.C., Jones, O., 2007. Heat stability of endogenous and microbial phytase during feed pelleting. Livest. Sci. 109, 244–246.
Simpson, D.J., Fincher, G.B., Huang, A.H.C., Cameron-Mills, V., 2003. Structure and function of cereal and related higher plant (1,4)-β-xylan endoxylanase. J. Cereal Sci. 37, 111–127.
Smeets, N., Nuyen, F., Van Campenhout, L., Niewold, T., 2014. Variability in the in vitro degradation of non-starch polysaccharides from wheat by feed enzymes. Anim. Feed Sci. Technol. 187, 110–114.
Sørensen, J.F., Kragh, K.M., Sibbesen, O., Delcour, J., Goesaert, H., Svensson, B., Tahir, T.A., Brufau, J., Perez-Vendrell, A.M., Bellincampi, D., D'ovidio, O., Camardella, L., Giovane, A., Bonnin, E., Juge, N., 2004. Review: potential role of glycosidase inhibitors in industrial biotechnological applications. Biochim. Biophys. Acta 1696, 275–287.
Sourdille, P., Perretant, M.R., Charmet, G., Leroy, P., Gautier, M.F., Joudrier, P., Nelson, J.C., Sorrells, M.E., Bernard, M., 1996. Linkage between RFLP markers and genes affecting kernel hardness in wheat. Theor. Appl. Genet. 93, 580–586.
Stenvert, N.L., Kingswood, K., 1977. The influence of the physical structure of the protein matrix on wheat hardness. J. Sci. Food Agric. 28, 11–19.
Stevens, B.J.H., Selvendran, R.R., Bayliss, C.E., Turner, R., 1988. Degradation of cell wall material of apple and wheat bran by human faecal bacteria in vitro. J. Sci. Food Agric. 44, 151–166.
Svihus, B., Gullord, M., 2002. Effect of chemical content and physical characteristics on nutritional value of wheat, barley and oats for poultry. Anim. Feed Sci. Technol. 102, 71–92.
Svihus, B., Klovstad, K.H., Perez, V., Zimonja, O., Sahlstrom, S., Schuller, R.B., 2004. Physical and nutritional effects of pelleting of broiler chicken diets made from wheat ground to different coarsenesses by the use of roller mill and hammer mill. Anim. Feed Sci. Technol. 117, 281–293.
Svihus, B., Uhlen, A.K., Herstad, O.M., 2005. Effect of starch granule structure, associated components and processing on nutritive value of cereal starch. A review. Anim. Feed Sci. Technol. 122, 303–320.
Tester, R.F., Karkalas, J., QI, X., 2004. starch structure and digestibility enzyme-substrate relationship. World's Poult. Sci. J. 60, 186–195.

Turnbull, K.M., Rahman, S., 2002. Endosperm texture in wheat. J. Cereal Sci. 36, 327–337.
Turnbull, K.M., Marion, D., Gaborit, T., Appels, R., Rahman, S., 2002. Temporal expression of grain hardness in the developing wheat endosperm. Planta 216, 699–706.
Verhoeven, T., Short, F., Weightman, R., Cowieson, A., Isaksen, M.F., 2005. Xylanase inhibitors in UK wheat varieties: survey of incidence and significance to pig and poultry feed. HGCA Res. Rev. 56.
Weurding, E., (Ph.D. thesis) 2002. Kinetics of Starch Digestion in Broilers. University of Wageningen.
Weurding, R.E., Enting, H., Verstegen, M.W.A., 2003. The effect of site of starch digestion on performance of broiler chickens. Anim. Feed Sci. Technol. 110, 175–184.
Wiseman, J., 2000. Correlation between physical measurements and dietary energy values of wheat for poultry and pigs. Anim. Feed Sci. Technol. 84, 1–11.
Wiseman, J., 2006. Variations in starch digestibility in non-ruminants. Anim. Feed Sci. Technol. 130, 66–77.
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.
Wu, Y.B., Ravindran, V., Thomas, D.G., Birtles, M.J., Hendriks, W.H., 2004. Influence of method of whole wheat inclusion and xylanase supplementation on the performance, apparent metabolisable energy, digestive tract measurements and gut morphology of broilers. Br. Poult. Sci. 45, 385–394.
Zyla, K., Gogol, D., Koreleski, J., Swiatkiewicz, S., Ledoux, D.R., 1999. Simultaneous application of phytase and xylanase to broiler feeds based on wheat: in vitro measurements of phosphorus and pentose release from wheats and wheat-based feeds. J. Sci. Food Agric. 79, 1832–1840.