Animal Feed Science and Technology xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Animal Feed Science and Technology

journal homepage: www.elsevier.com/locate/anifeedsci

Review

Interactions between wheat characteristics and feed enzyme supplementation in broiler diets

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ARTICLE INFO

Article history:
Received 15 May 2014
Received in revised form 4 August 2014
Accepted 12 September 2014
Available online xxx

Keywords:
Wheat quality
Hardness
Enzymes
Broilers
Feed form

ABSTRACT

Wheat is a very variable grain in terms of its physical and chemical characteristics. Of its physical characteristics, hardness appears to be the most important quality, having the greatest influence on broiler performance and nutrient digestibility. The effect of wheat hardness on broiler performance is also likely to be influenced by feed form (e.g. mash versus pelleted feed). For the chemical characteristics, the level and structure of the non starch polysaccharides (NSP) are important criteria in determining the feeding quality of the wheat. With regard to enzyme response, most research has focused on the chemical structure, in particular NSP level of the wheat with little attention on the importance of the physical quality. Further studies are required to better understand the effect of physical qualities of wheat and how they influence the response to feed enzymes. This review sheds light on some of the chemical and physical wheat quality that may affect enzyme response in broilers.

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1. Introduction

Wheat is a major energy source in broiler feeds in many parts of the world, including Europe, Canada, Australia and New Zealand. However, the physical and chemical composition of wheat is highly variable, making it one of the most variable cereal grains (Choct et al., 1999). Commercially, wheat can account for up to 70% of the metabolisable energy and 35% of the protein requirements of broilers. Therefore, variation in the quality of the wheat is expected to have a major impact on the performance of chickens (Gutierrez del Alamo et al., 2008). The variation in broiler performance when feeding different

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http://dx.doi.org/10.1016/j.anifeedsci.2014.09.012
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Please cite this article in press as: Amerah, A.M., Interactions between wheat characteristics and feed enzyme supplementation in broiler diets. Anim. Feed Sci. Tech. (2014), http://dx.doi.org/10.1016/j.anifeedsci.2014.09.012

Table 1
Chemical composition of wheat (g/kg)[a].

	Average	Range
Protein	120	80–201
Starch	585	402–712
Amylose: amylopectin	0.466	–
Fat	20	9–34
Ash	16	15–18
Water-insoluble cell walls	102	94–118
Non-starch polysaccharide		
Total	115	66–146
Soluble	28	8–41
Insoluble	87	
Pentosans		45–61
Arabinoxylans		
Soluble	18	
Insoluble	63	
Total P	3.6	2.3–8.3
Phytate P	2.8	0.9–3.2
Endogenous enzymes		
Xylanase XU[c]	0.48	0.27–0.64
Phytase (FTU/kg)	508	206–775
α-Amylase activity (AU)[d]	0.12	
Lipase[b]	7.93	2.0–27.3
Xylanase inhibitors[e]		
TAXI	94	17–137
XIP	299	234–355
Xylanase inhibition activity (InhU)[d]	183	

[a] From Barrier-Guillot et al. (1996b), Rose et al. (2001), Carre et al. (2002) Svihus and Gullord (2002), Gys et al. (2004), Choct (2006) and Ravindran and Amerah (2009).
[b] Degradation percentage of 1.9 g rapeseed oil mixed with 15 g of wheat ground on 3 mm screen after 4 weeks at ambient temperature (Carre et al., 2002).
[c] One enzyme unit is the amount of enzyme needed to increase the extinction at 590 nm (E590) by 1 per hour of incubation under the conditions of the assay (Dornez et al., 2006).
[d] Gys et al. (2004).
[e] Dornez et al. (2006); TAXI (*Triticum aestivum* xylanase inhibitor); XIP (xylanase inhibitor protein).

wheats was attributed, in most studies, to the high variability in chemical composition, in particular the level of non starch polysaccharide (NSP; Wiseman, 2000). Physical characteristics of the wheat are also important criteria which may influence broiler performance (Rose et al., 2001; Peron et al., 2006; Carre et al., 2007) but have attracted less attention in the literature. For example, in terms of feed processing and feeding value, whether a grain is hard or soft is of great importance (Amerah et al., 2007).

Xylanase supplementation to broiler diets is a common practice to alleviate the adverse effects of NSP and to minimise the variation in apparent metabolisable energy (AME) and performance of poultry fed wheat-based diets (Bedford, 1996; Hughes and Choct, 1999). However, there is a variable response to enzyme supplementation when added to wheat based diets (Gutierrez del Alamo et al., 2008), which may be explained, in part, by the diverse and complicated nature of the carbohydrate fraction and linkage between nutrients and the cell wall structure (Kim et al., 2005). Physical structure of the wheat may also explain partly the variable responses to enzyme supplementation (Carre et al., 2007; Amerah et al., 2009). Other factors that may cause variation in response include, feed processing, xylanase molecule properties, breed and age of birds (Bedford, 1997; Amerah et al., 2011). The aim of the present paper is to review available data on the effects of physical and chemical composition of wheat on the efficacy of exogenous enzymes.

2. Wheat chemical composition

The chemical composition of wheat of a given type and variety varies from year to year depending upon area, growing location, use of fertilizer, moisture conditions and other agronomic factors (Ravindran and Amerah, 2009). However, the intrinsic factors in wheat that cause this variation are not yet completely established (Svihus and Gullord, 2002). A summary of the chemical variation of wheat from selected publications is presented in Table 1. For example, Svihus and Gullord (2002) compared 16 samples of Norwegian wheats, reported variation in starch content between 614 g/kg and 712 g/kg, protein between 109 g/kg and 154 g/kg, fat between 22 g/kg and 34 g/kg, crude fibre between 20 g/kg and 26 g/kg and, sugar between 16 g/kg and 55 g/kg.

The AME value of the wheat depends on the content and digestibility of starch, protein and lipids (McCracken and Quintin, 2000; Svihus and Gullord, 2002; Wiseman, 2006; Carre et al., 2007). Starch is the most abundant carbohydrate in wheat and the main energy-yielding component. The starch content varies from 60 to 75% and is inversely related to the protein content of the wheat (Pirgozliev et al., 2003; Ravindran and Amerah, 2009). However, the digestibility of starch in the wheat may vary according to starch structure, amylose to amylopectin ratio and interactions with other components of the endosperm

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and with processing conditions (Svihus et al., 2005). Interestingly, Carre et al. (2007) estimated the range of digestibility variations between broilers fed wheat based diets (50% wheat in the diet) to be about 15, 10 and 3% for lipids, starch and proteins, respectively. Digestion of wheat lipid is strongly related to grain viscosity, and high levels of soluble NSP result in a reduction in fatty acids absorption (Carre et al., 2007). For starch, it appears that the rate of starch digestion (RSD) is the important factor affecting bird performance (Gutierrez del Alamo et al., 2008; Ball et al., 2013). Gutierrez del Alamo et al. (2008) reported that broiler growth and feed conversion ratio improved in a quadratic way with RSD. Similarly, Ball et al. (2013) found a positive correlation between RSD and performance parameters. The RSD may influence the insulin level in the blood, glucose availability and consequently protein accretion (Weurding, 2002). In contrast, using other feed ingredients (not including wheat), Weurding et al. (2003) reported that broiler chickens perform better on diets containing high amount of slowly digestible starch. These apparent conflicting results between wheat and other ingredients may relate to other chemical and physical characteristics of the feed ingredients.

Protein level in wheat is higher compared to corn and the amino acid concentrations of the wheat increase linearly with increasing wheat protein levels. However, the level of protein in wheat is variable and the content of commercial wheat varieties range from 8 to 16%, depending on variety and growing conditions (Lasztity, 1999). Ravindran et al. (2005) reported that lysine and threonine are the least digestible essential amino acids and most likely to be deficient when chickens are fed wheat-based diets. Svihus and Gullord (2002) reported a negative correlation between protein content and AME values which may be caused by an inhibitory effect of the protein matrix on availability of starch in the endosperm or the lower content of starch in these wheat varieties.

It is well documented that the level and structure of NSP is very variable in wheat (Knudsen, 1997; Pirgozliev et al., 2003; Smeets et al., 2014). However, the main component of NSP in wheat is arabinoxylan (Table 1). Soluble and insoluble NSPs in wheat have different properties and consequently different effects on digestion in poultry. Most of the arabinoxylans in wheat are insoluble because they are anchored to the cell walls by alkali-labile ester-like cross links (Choct, 1997). The negative effect of NSP on nutrient utilisation and birds performance is well documented (Choct, 2006). Two major mechanisms have been proposed to explain the anti-nutritional effects of NSP (Bedford and Schulze, 1998). The first mechanism is associated with the fact that starch and protein are encapsulated by the cell wall in wheat endosperm cells. The second mechanism relates to the viscous nature of digesta caused by the soluble NSPs. High soluble NSP is known to increase digesta viscosity and reduce nutrient digestibility and performance (Choct and Annison, 1992; Choct et al., 1995). Intriguingly, Ball et al. (2013) reported a positive relationship between *in vitro* viscosity and dry matter intake, weight gain, gain per feed and *in vivo* viscosity.

The anti-nutritional effect of phytate is well documented in the literature and, like all other cereal grains, phytate is also present in wheat (Selle and Ravindran, 2007). However, there is a wide variation of phytate-P level between wheat samples according to cultivar and growing conditions. As evidenced by Selle et al. (2003) the range of phytate P contained in 37 Australian wheat samples varied more than two-fold from 1.35 g/kg to 3.20 g/kg with an average of 2.20 g/kg. The 'phytate effect' in feedstuffs is known to reduce nutrient utilisation and therefore increase the production cost and the environmental impact (Selle and Ravindran, 2007). The chemical structure of phytate as a polyanionic molecule with the affinity to chelate positively charged nutrients contributes to its anti-nutritive properties (Selle and Ravindran, 2007). The phytate protein interaction in the upper digestive tract at low pH has been suggested to be responsible for the compromising effect of phytate on Na, Ca, amino acids, and energy digestion (Adeola and Cowieson, 2011). On the other hand, in the small intestine at higher pH, phytate interact with divalent cations forming insoluble precipitates, which effectively reduce their digestibility (Adeola and Cowieson, 2011). These anti-nutritional effects, present in wheat, have been largely overcome by the use of appropriate feed enzymes.

Endogenous enzymes in wheat are part of the chemical composition that has received little attention in the literature. Endogenous enzymes in wheat kernel are responsible for releasing energy for growth and developing the embryo when sprouting begins (Stevens et al., 1988). Xylanases are present in wheat (Bonnin et al., 1998; Cleemput et al., 1995) with a main function of degrading the walls of aleurone and endosperm cells during the germination stage making starch and storage proteins accessible to aleurone derived amylases and proteases (Mares and Stone, 1973a,b). Apparent xylanase activities in wheat are, in part, dependent on genetic background (Dornez et al., 2006). Endogenous phytase activity is also present in wheat to increase the availability of bound phosphorus (Barrier-Guillot et al., 1996b) which may explain the higher availability of wheat phosphorus for poultry in comparison to many other feedstuffs (Barrier-Guillot et al., 1996a). Zyla et al. (1999) reported a highly significant correlation between endogenous phytase activity in wheats and amounts of phosphorus released during *in vitro* digestion. Endogenous phytase and xylanase activity of hard red spring (HRS) wheat were found to be 44 and 29% higher respectively than those of durum samples which may result in significantly better P digestibility in HRS wheat-based diets in broiler chickens (Afsharmanesh et al., 2008). However, endogenous enzymes are heat labile (Silversides and Bedford, 1999; Scott et al., 2003; Slominski et al., 2007) which may reduce their importance in broiler diets since most diets are fed in pelleted form (Amerah et al., 2007). Afsharmanesh et al. (2008) reported that inactivation of endogenous phytase by the heat treatment was 60 and 38% for durum and HRS wheat, respectively.

Wheat contains endo-xylanase inhibitors to regulate the hydrolysis of kernel arabinoxylan and inhibit exogenous enzymes produced by microorganisms (Simpson et al., 2003). Two types of endo-xylanase inhibitors that are structurally different have been reported in the literature, namely, *Triticum aestivum* xylanase inhibitor (TAXI)-type and xylanase inhibitor protein (XIP; Sørensen et al., 2004, Bedford, 2006). The level of these inhibitors in wheat differs according to cultivar (Dornez

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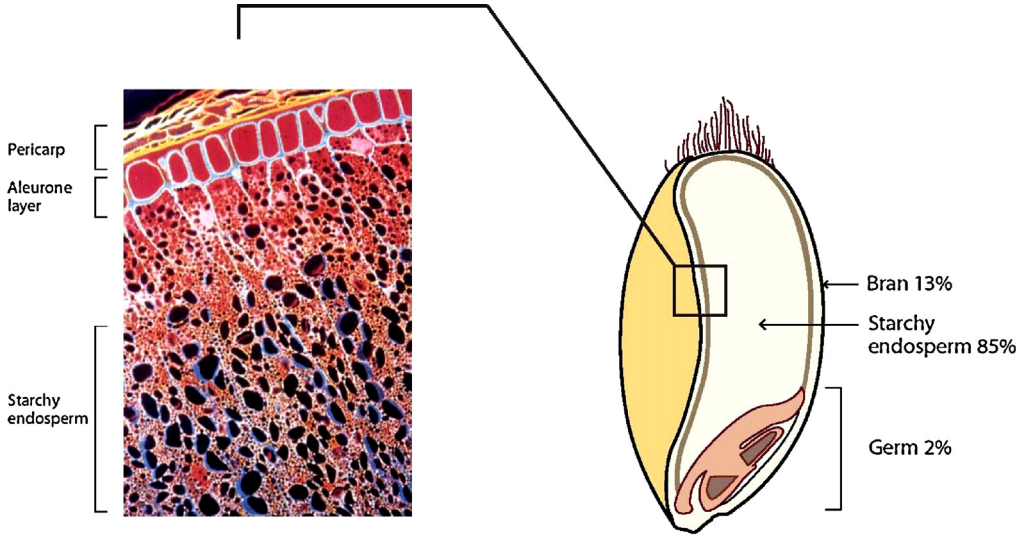

Fig. 1. Wheat kernel.

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

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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

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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.

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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.

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Please cite this article in press as: Amerah, A.M., Interactions between wheat characteristics and feed enzyme supplementation in broiler diets. Anim. Feed Sci. Tech. (2014), http://dx.doi.org/10.1016/j.anifeedsci.2014.09.012

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Please cite this article in press as: Amerah, A.M., Interactions between wheat characteristics and feed enzyme supplementation in broiler diets. Anim. Feed Sci. Tech. (2014), http://dx.doi.org/10.1016/j.anifeedsci.2014.09.012

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