Energy utilization and growth performance of chickens fed novel wheat inbred lines selected for different pentosan levels with and without xylanase supplementation

V. Pirgozliev,[*1] S. P. Rose,[*] T. Pellny,[†] A. M. Amerah,[‡] M. Wickramasinghe,[†,§] M. Ulker,[†,#] M. Rakszegi,[‖] Z. Bedo,[‖] P. R. Shewry,[†] and A. Lovegrove[†]

[*]*NIPH, Harper Adams University, Shropshire, TF10 8NB, UK;* [†]*Rothamsted Research, West Common, Harpenden, AL5 2JQ, UK;* [‡]*Danisco Animal Nutrition, Wiltshire, SN8 1XN, UK;* [§]*University of Peradeniya, 20400, Sri Lanka;* [#]*Yuzuncu Yil University, Van, Turkey; and* [‖]*Centre for Agricultural Research, MTA, Martonvásár, Hungary*

ABSTRACT Different F5 recombinant inbred lines from the cross Yumai 34 × Ukrainka were grown in replicated trials on a single site in one harvest year at Rothamsted Research. A total of 10 samples from those lines were harvested and used in a broiler experiment. Twenty nutritionally complete meal-form diets that had 630 g/kg of wheat with different amounts of pentosan, with and without exogenous xylanase supplementation, were used to compare broiler growth performance and determine apparent metabolizable energy corrected for N retention (AMEn). We examined the relationship between the nutritive value of the wheat samples and their chemical compositions and results of quality tests. The amounts of total and water soluble pentosans in wheat samples ranged from 36.7 to 48.0 g/kg DM, and 6.7 to 11.6 g/kg DM, respectively. The mean crude oil and protein contents of the wheat samples were 10.5 and 143.9 g/kg DM, respectively. The average determined value for the kinematic viscosity was 0.0018 mPa.s, and 2.1 mPa.s for the dynamic viscosity. The AMEn of the wheat-based diets had a maximum range of 0.47 MJ/kg DM within the ten wheat samples that were tested. Xylanase supplementation improved ($P < 0.05$) dietary AMEn, dry matter, and fat digestibility coefficients. There was a positive ($P < 0.05$) relationship between *in vitro* kinematic viscosity of the wheat samples and the total pentosan content. There was a negative relationship between the total pentosan content in the wheat and broiler growth performance. An increase by 10 g of pentosan per kg of wheat reduced ($P < 0.001$) daily feed intake and weight gain by 2.9 g and 3.5 g, respectively. The study shows that the feeding quality of wheat samples can be predicted by their total pentosan content. Supplementary xylanase improved energy and nutrient availability of all wheat samples that was independent of differences in pentosan content.

Key words: wheat pentosan, xylanase, viscosity, broiler

2015 Poultry Science :1–8
http://dx.doi.org/10.3382/ps/peu059

INTRODUCTION

The high yield, low cost, and relatively high amount of available energy make wheat one of the most used raw material for poultry feeds in North West Europe, the Americas, and Australasia. Approximately 700 million tons of wheat are produced in the world each year, and approximately 20% of it is used as animal feed (International Grain Council, 2013). Wheat is often the only cereal used in broiler feed formulations and can comprise up to 800 g/kg of the diet for finishing broilers (Wiseman and Inborr, 1990). Thus the nutritional value of wheat and variation in its feeding quality are commercially important.

Although much research on the feeding quality of wheat has been carried out (Gutiérrez-Alamo et al., 2008; Ball et al., 2013), there is little conclusive information on how the chemical composition and quality parameters of different wheat grain samples relate to their metabolizable energy content and the growth performance of poultry. In particular, reports of the relationships between the growth of poultry and the characteristics of the wheat grain, such as endosperm hardness, specific density, Hagberg falling number, viscosity, proximate analysis, and metabolizable energy, have been contradictory (McCracken et al., 2001; Rose et al., 2001; Steenfeldt, 2001; Carré et al., 2002; Pirgozliev et al., 2003).

However, research has also indicated that the low available apparent metabolizable energy (AME) of some wheats is related to their high contents of nonstarch polysaccharides (NSP) (Annison, 1991; Choct

Received May 29, 2014.
Accepted October 20, 2014.
[1]Corresponding author: vpirgozliev@harper-adams.ac.uk

et al., 1999; Ball et al., 2013), which inhibit the digestion of starch, lipid, and protein in the small intestine (Choct and Annison, 1990; Steenfeldt, 2001).

NSPs have a structural function as the main components of plant cell walls, and account for approximately 10% of the whole grain in wheat (Annison, 1991). The majority of NSPs in wheat are pentosans, which accounts for about 6% of the grain dry weight (Stone and Morell, 2009). The anti-nutritive properties of wheat NSPs have been well documented, (Annison, 1991; Choct and Annison, 1990; Steenfeldt, 2001) with their high viscosity contributing to their negative effects. Diets are therefore often treated with NSP-degrading enzymes to reduce viscosity and improve nutrient availability and the growth performances of broilers (Olukosi et al., 2007). However, breeding wheat cultivars with reduced NSP content (and hence viscosity) may also be an option to improve the feeding quality of wheat for poultry.

Choct and Annison (1990) compared diets with a relatively wide range of NSP contents by adding extracted pentosans to wheat samples and comparing the AME of different cereals. In the first experiment, researchers demonstrated that NSP levels could become modified during the extraction, thereby altering its solubility and properties. Further experiments demonstrated that comparing the nutrient digestibility and available energy of different cereals, or even varieties of individual cereal species, in relation to NSP content, are even more difficult to carry out because of significant differences in grain composition and structure. These confounding effects could be eliminated by the use of near-isogenic lines of wheat that differ primarily in pentosan content. Such lines have random contributions of characteristics from the parental genotypes, allowing the trait of interest to be studied independently of background effects. These lines would also provide the opportunity to directly evaluate the effect of exogenous xylanase supplementation on the nutritive value of wheats with different levels of pentosan.

We have therefore compared 10 lines derived from a cross between wheat genotypes which were identified as high and low in both total and soluble pentosans (Gebruers et al., 2008). These lines were incorporated into nutritionally complete diets for broiler chickens with and without xylanase supplementation, allowing the birds performance to be related to their content of total pentosans, and in particular to the viscosity resulting from total pentosans.

MATERIALS AND METHODS

Wheat Samples

The wheat cultivars Yumai 34 and Ukrainka were identified as having unusually high and low contents of total and soluble pentosans, respectively, as part of a broad screen of 150 wheat lines (Gebruers et al., 2008) carried out under the EU FP6 HEALTHGRAIN program (Poutanen et al., 2008). Ten F5 lines were therefore selected from this population to represent a range of pentosan content levels and grown together at Rothamsted from 2011–12. The growing sites were split into land blocks, with the wheat cultivars sown in a randomized design within each block. Standard agronomy was used with 200 kg N/Ha.

Proximate Analysis of Wheat Samples

Dry matter (DM) in wheat was determined by drying of samples in a forced draft oven at 105°C to a constant weight. Ash was measured in a muffle furnace at 500°C for 18 h. Crude protein (6.25 X N) in wheat was determined by the combustion method (AOAC, 2000) using a Leco (FP-528 N, Leco Corp., St. Joseph, MI). Oil (as ether extract) was extracted with diethyl ether by the ether extraction method (AOAC, 2000) using a Soxtec system (Foss UK Ltd.). The gross energy (GE) value of wheat samples was determined in a bomb calorimeter (model 6200; Parr Instrument Co., Moline, IL) with benzoic acid used as the standard.

Pentosan Content and Viscosity of the Experimental Wheat Samples

Total (TP) and water extractable (WP) pentosans in the whole grain were determined as described by the method of Finnie et al. (2006) and Douglas (1981). Kinematic water extracted viscosity (KV) was measured using an automated viscometer (AVS 310 Schott Gerate, Germany) fitted with an Oswald capillary tube. Dynamic water extracted viscosity (DV) was measured with a rotating cone and cup viscometer (model DV-II + LV Brookfield, Stroughton, MA, USA).

Grain Quality Analysis

Hagberg falling number (HFN) was measured by Hagberg falling number apparatus model 1800 (Falling Number AB, Stockholm, Sweden) (AOAC, 2000). Endosperm hardness was determined by the single-kernel characterization system (SKCS) model 4100 (Perten Instruments North America, Inc., Reno, NV). Specific density (kg/hl) of wheat samples was measured with a chondrometer (Farm Tech, Whitby, UK).

Determination of Dietary Metabolizable Energy, Nutrient Digestibility and Comparison of Broiler Growth Performance

All procedures were approved by The Animal Experimental Committee of Harper Adams University.

Ten diets containing 630 g/kg of each of the ten experimental wheat samples were prepared after mixing with 370 g/kg of a balancer (Table 1). Each diet was then split into two equal batches and one of them

Table 1. Ingredient composition (g/kg, as-fed) of the experimental balancer formulation.

Dietary ingredients	kg/100kg
Soybean meal (48)	64.86
Maize gluten meal	12.62
Vegetable oil	10.27
Dicalcium phosphate	5.00
Limestone	2.84
NaCl	0.76
Lysine HCL	0.95
Methionine	1.35
Vitamin mineral premix[1]	1.35
	100
Calculated analysis	
Crude Protein g/kg	414.2
ME MJ/kg	12.77
Crude Fat g/kg	110.1
Ca g/kg	24.5
Available P g/kg	10.4
Digestible Lysine g/kg	37.8
Digestible Methionine + Cysteine g/kg	11.2
Digestible Tryptophan g/kg	4.1
Digestible Threonine g/kg	13.5

This balancer was fed as a part of complete diet comprised 630 g/kg of each experimental inbred wheat line sample and 370 g/kg of the balancer. Each experimental diet met the diet specification for this strain of broiler chicken (Aviagen Ltd., Edinburgh, UK).

[1]The vitamin and mineral premix contained vitamins and trace elements to meet the breeder's recommendations (Aviagen Ltd., Edinburgh, UK). The premix provided (units/kg complete diet (63% wheat and 37% balancer)): retinol 3600 mg, cholecalciferol 125 mg, α-tocopherol 34 mg, menadione 3 mg, thiamine 2 mg, riboflavin 7 mg, pyridoxine 5 mg, cobalamin 15 mg, nicotinic acid 50 mg, pantotenic acid 15 mg, folic acid 1 mg, biotin 200 mg, iron 80 mg, copper 10 mg, manganese 100 mg, cobalt 0.5 mg, zinc 80 mg, iodine 1 mg, selenium 0.2 mg and molybdenum 0.5 mg.

was supplemented with 2000 units/kg of a commercial xylanase (Danisco Xylanase, Danisco Animal Nutrition, Marlborough, UK), resulting in 20 diets in total. The enzyme preparation was based on endo-1,4-beta-xylanase produced by *Trichoderma reesei*. No adjustments were made for differences in dry matter between the wheat samples because only a small range of differences were observed.

The objectives of the broiler feeding experiment were to compare the growth performance of broilers and determine the AME corrected for N retention (AMEn) in diets containing the experimental wheat samples with and without enzyme supplementation. Male Ross 308 broiler chickens were obtained from a commercial hatchery at one-day old and were placed in a single floor pen and fed on a proprietary broiler starter feed until 6 d of age. On the first day of the experimental period (at 7 d of age), the chicks were individually weighed and randomly placed in one of the experimental pens. Two birds were placed in each pen (0.4m X 0.4m solid floor area) within a controlled environment room. Each diet was fed at random to 6 pens from 7 to 21 d age. The temperatures were kept at 30°C until the chickens were 7 d of age and were gradually reduced to 20°C at the end of the 14 d feeding period. A standard lighting program for broilers was used, decreasing the light:dark ratio from 23h:1h from day old to 18h:6h at 7 d of age, which was maintained until the end of the study. Access to the feed and the water was *ad libitum*.

During the last four days of the experiment, the solid floor of each pen was replaced with a wire mesh and all excreta were collected and immediately dried at 60°C and then milled. Feed intakes were also measured for the same period. The gross energy, dry matter, nitrogen, and fat of each dried excreta sample and the experimental diets were determined as described for the wheat samples. The AMEn of the diets was calculated as described by Hill and Anderson (1958). The coefficients of total tract fat digestibility (FD), dry matter (DMR) and nitrogen retention (NR) were determined as the difference between intake and excretion (retention) of the nutrient divided by their respective intake.

The concentration of mucin in the excreta, measured as sialic acid (SA), was determined by the periodate-resorcinol method described by Jourdian et al. (1971).

On the last day of the feeding period at 21 d of age, the birds were weighed and killed by cervical dislocation. The contents from the bottom of the duodenal loop to Meckel's diverticulum of the digestive tracts of both birds in one pen were immediately collected and pooled, then centrifuged (10 000g for 2 min) and their viscosity measured as described by Bedford and Classen (1992).

Statistical Procedures

Statistical analyses were performed using the Genstat statistical software package (Genstat 15th release 3.22 for Windows; IACR, Rothamstead, Hertfordshire, UK). The AMEn content of the experimental diets, broiler growth performance, nutrient digestibility, and digesta viscosity were compared statistically by analysis of variance using a 10×2 factorial arrangement of treatments. The main effects analyzed were related to the effects of the pentosan content of the wheats with and without xylanase. The comparison between the experimental results was performed by ANOVA, and the treatment sum of squares was partitioned into orthogonal contrasts testing for the linear and quadratic responses to total pentosan content of wheat and their interactions with the addition of exogenous xylanase. Correlation coefficients were also generated to determine if there is a relationship between the wheat pentosans, viscosity, and growth performance variables. The data from the animal experiments were substituted by their standardized residuals; this eliminated the effects of the dietary enzyme. In all instances, differences were reported as significant at $P < 0.05$. Tendencies towards significance ($0.05 < P < 0.1$) were also reported.

RESULTS

Characteristics of the Wheat Lines

The grain compositions are summarized in Table 2.The amounts of oil and protein were more variable than the contents of ash and GE, and ranged from 8.0 to 13.9 g/kg DM and 131 to 162 g/kg DM, respectively. The mean total pentosan content of the wheat samples was 43.5 g/kg, which was comprised of 9 g/kg DM of soluble pentosans and 34.5 g/kg of insoluble pentosans (Table 2). The average determined value for the KV was 0.0018 mPa.s, and for the DV was 2.1 mPa.s.

The average specific density and weight of 1000 grains were 77.3 kg/hl and 39.7 g, respectively (Table 2). The values of the HFN were most variable, ranging from 71 to 239 s. The average endosperm hardness of the wheat samples was 68.5, ranging from 63 to 74 relative units.

Broiler Growth Performance, Dietary Metabolizable Energy and Nutrient Digestibility

Variation in feed intake, weight gain, and feed efficiency were in the expected range (coefficient of variation (CV) = 10.9%, 11.4%, and 8.2%, respectively) for 7 to 21 d old broiler chickens (Table 3). The variation in dietary AMEn was relatively low (CV = 3%), ranging from 13.14 to 13.47 MJ/kg DM and was not affected by pentosan content ($P > 0.05$). Feeding exogenous xylanase improved ($P < 0.05$) dietary AMEn by 0.19 MJ/kg DM, or by 1.4%. Daily intake of dietary AME tended ($P = 0.072$) to increase with supplementary xylanase.

Nutrient retention and digestibility coefficients were not affected ($P > 0.05$) by wheat pentosan content (Table 4). The CV in dry matter (DMR) and nitrogen (NR) retention, and fat (FD) digestibility coefficients were 3.8%, 6.7% and 4.3%, respectively. Dietary xylanase improved ($P < 0.05$) DMR and FD by 2.4% and by 2%, respectively, but did not affect ($P > 0.05$) the NR coefficient.

Concentration of SA in excreta tended ($P = 0.067$) to be affected by wheat pentosan content but did not follow a consistent pattern ($P > 0.05$). Data on digesta viscosity were variable (CV = 42.2%) and ranged between 1.71 mPa.s and 3.06 mPa.s. Digesta viscosity were affected by wheat pentosans, but like SA, there was no consistent pattern ($P > 0.05$).

Relationship Between Chemical Composition of the Wheat, Dietary Metabolizable Energy and Chicken Growth Performance

A high pentosan content reduced the birds' daily feed intake and weight gain, which was best described as a linear response as total pentosans increased (Table 3). An increase by 10 g of pentosan per kg wheat reduced

Table 2. Chemical composition, viscosity and grain quality analysis of the experimental inbred wheat lines.

Wheat sample	Dry matter (kg/kg)	Ash (g/kg DM)	Oil (g/kg DM)	Protein (g/kg DM)	Gross energy (MJ/kg DM)	Total pentosans (g/kg)	Water soluble pentosans (g/kg)	Kinematic viscosity (mPa.s)	Dynamic viscosity (mPa.s)	Specific density (kg/hectolitre)	Weight of 1000 grains (g)	Hagberg falling number (s)	Endosperm hardness (relative units) (range 0 to 100) (soft—hard)
Wheat A	0.871	14.1	13.8	137	18.17	36.7	8.1	0.0016	2.4	75.26	37.9	175	66
Wheat B	0.872	18.0	8.0	141	18.13	38.1	8.7	0.0017	1.78	78.64	43.3	200	67
Wheat C	0.872	18.0	10.3	141	18.06	40.8	9.7	0.0017	3.06	78.21	43.6	71	63
Wheat D	0.862	17.0	11.6	131	18.04	41.3	6.7	0.0014	2.06	79.57	34.5	239	69
Wheat E	0.869	17.1	8.1	162	18.07	44.7	9.4	0.0021	2.26	76.41	40.6	161	68
Wheat F	0.869	15.1	11.5	147	18.29	45.8	8.8	0.0018	2.19	77.91	41.5	195	70
Wheat G	0.872	19.0	10.3	144	18.15	46.7	11.6	0.0023	1.8	78.76	39.2	221	74
Wheat H	0.872	18.0	10.3	147	18.21	47.0	10.1	0.0019	1.71	76.81	38.2	132	69
Wheat I	0.874	19.0	10.3	149	18.11	47.2	9.6	0.0020	1.76	75.69	41.5	180	68
Wheat J	0.871	19.0	10.3	140	18.15	48.0	7.6	0.0016	2.39	75.75	37.3	72	71

($P < 0.001$) daily feed intake and weight gain by 2.9 g and 3.5 g, respectively (Table 5). Feed efficiency was not affected ($P > 0.05$) by pentosan content, and feeding exogenous xylanase did not influence ($P > 0.05$) the growth performance of the birds.

Birds daily feed intake was negatively ($P < 0.05$) correlated with the KV (Table 6). Total pentosan content of wheat was negatively correlated to daily feed intake ($P < 0.05$), weight gain ($P < 0.001$), and FCE ($P < 0.1$).

Table 3. The effect of wheat total pentosan content and xylanase supplementation on daily bird feed intake (FI), weight gain (WG), feed efficiency (FE), dietary apparent metabolisable energy corrected for N retention (AMEn), and daily AMEn intake

Treatment factor	FI (g DM/b/d)	WG (g/b/d)	FE (g gain: g feed)	AMEn (MJ/kg DM)	AMEn int (MJ/d)
Total pentosans (g/kg)					
36.7	53.7	41.1	0.766	13.17	0.71
38.1	56.0	42.2	0.754	13.38	0.75
40.8	52.2	37.9	0.727	13.27	0.69
41.3	53.9	40.2	0.747	13.30	0.72
44.7	51.7	38.7	0.751	13.36	0.69
45.8	53.3	38.2	0.718	13.61	0.73
46.7	50.4	37.5	0.745	13.27	0.67
47.0	51.9	38.0	0.737	13.14	0.68
47.2	52.0	37.7	0.730	13.47	0.70
48.0	51.5	37.8	0.737	13.39	0.69
SEM	1.65	1.28	0.0176	0.117	0.025
Xylanase					
No	52.0	38.4	0.741	13.24	0.69
Yes	53.4	39.4	0.741	13.43	0.72
SEM	0.74	0.574	0.0079	0.052	0.011
Statistical probabilities of treatment differences					
Total pentosans	0.510	0.120	0.746	0.203	0.557
Linear effects	0.033	0.001	0.148	0.277	0.102
Quadratic effects	0.975	0.587	0.398	0.495	0.939
Xylanase	0.184	0.215	0.957	0.012	0.072
Total pentosans x Xylanase	0.564	0.949	0.135	0.209	0.367

There were 6 observations per treatment.

There is a statistically significant difference when $P < 0.05$; SEM – Standard errors of means.

Growth performance data is based on feeding period from 7 to 21d age. Data on AMEn is based on four days collection period (18, 19, 20, 21d age).

Table 4. The effect of wheat total pentosan content and xylanase supplementation on coefficients of dietary dry matter (DMR) and nitrogen retention (NR), fat digestibility (FD), sialic acid concentration (SAc) and ileal digesta viscosity

Treatment factor	DMR (g ret: g int)	NR (g ret: g int)	FD (g ret: g int)	SA c (μg / g)	Digesta viscosity (mPa.s)
Total pentosans (g/kg)					
36.7	0.704	0.621	0.864	1.216	2.40
38.1	0.715	0.627	0.847	1.212	1.78
40.8	0.712	0.633	0.876	1.132	3.06
41.3	0.715	0.636	0.871	1.217	2.06
44.7	0.719	0.628	0.860	1.225	2.26
45.8	0.726	0.643	0.884	1.185	2.19
46.7	0.703	0.627	0.848	1.151	1.80
47.0	0.697	0.619	0.863	1.145	1.71
47.2	0.728	0.656	0.885	1.285	1.76
48.0	0.716	0.629	0.860	1.166	2.39
SEM	0.0079	0.0123	0.0106	0.0341	0.261
Xylanase					
No	0.705	0.628	0.857	1.194	2.50
Yes	0.722	0.636	0.874	1.192	2.03
SEM	0.0035	0.0055	0.0048	0.0153	0.117
Statistical probabilities of treatment differences					
Total pentosans	0.129	0.638	0.132	0.067	0.011
Linear effects	0.495	0.422	0.502	0.602	0.146
Quadratic effects	0.297	0.503	0.295	0.672	0.232
Xylanase	0.002	0.295	0.012	0.932	0.185
Total pentosans x Xylanase	0.375	0.408	0.180	0.281	0.370

There were 6 observations per treatment.

There is a statistically significant difference when $P < 0.05$; SEM – Standard errors of means.

Data on nutrient retention/digestibility coefficients and SA excretions is based on four days collection period (18, 19, 20, 21d age) and was calculated by dividing retained (g ret) nutrients by the nutrient intake (g int) for the collection period.

Data on ileal digesta viscosity is based on digesta collection at the end of the study (21d age).

Table 5. Relationship between wheat total pentosan content and feed intake and weight gain

Dependent variate	Constant	Total pentosans	r^2	SEO
Feed intake (g DM/b/d)	65.45 (± 3.95) <0.001*	− 0.293 (± 0.090) 0.012*	0.57	1.11
Weight gain (g/b/d)	54.01 (± 3.18) <0.001*	− 0.346 (± 0.073) 0.001*	0.74	0.891

*Student's t-test for the constant and independent variables.
SEO – Standard error of observations ($n = 10$).

Dietary AMEn did not correlate ($P > 0.05$) to any of the determined variables. The KV of the wheat was positively correlated to WSP ($P < 0.001$) and TP ($P < 0.1$).

DISCUSSION

The study evaluated the feeding quality of novel inbred wheat lines. Chemical composition of wheat varies due to a number of major factors, including crop husbandry /crop nutrition, location, seasonal factors (including rain fall, temperature, diseases), and genetics (Kettlewell et al., 1999; Porter and Semenov, 2005; Peng et al., 2011). The novel aspect of this experiment was that the experimental wheat samples were produced in a randomized block experiment on one site in one location in one growing year.

Commercial wheat varieties have been selected for a large number of traits that often interact with seasonal variables. The present experiment used isogenic lines that were primarily selected for their pentosan content. This experiment was therefore able to give clear evidence of the importance of wheat pentosan content on the nutritional value of wheat grown for poultry feed.

The proximate nutrient, pentosan, *in vitro* viscosity, and GE content of the 10 wheat samples were in a similar range to those measured in other studies (Pirgozliev et al., 2003; Gebruers et al., 2008; Amerah et al., 2009; Ball et al., 2013). The range of pentosan contents was consistent with segregation between the high and low pentosan contents of the two parental varieties (Gebruers et al., 2008).

The samples also differed in HFN, which presumable reflected differences between the susceptibility of the two parental varieties to either pre-harvest sprouting or pre-maturity amylase production.

The pentosan content in wheat, especially the soluble fraction, has been described as a major factor responsible for the variable responses observed when exogenous xylanase is added to poultry diets (Bedford and Classen, 1992). Studies of the mechanisms by which exogenous enzymes enhance nutrient digestion and utilization in wheat, suggest that the growth performance and dietary metabolizable energy response to enzyme supplementation may be associated with various factors, including changes in digesta viscosity, microbial proliferation, hind gut fermentation, and eliminating the nutrient encapsulating effect of the plant cell wall (Choct and Annison, 1992; Choct et al., 1996; Langhout et al., 2000).

Ileal digesta viscosity was in the expected range (Choct et al., 1999; Pirgozliev et al., 2003) but was not significantly reduced ($P > 0.05$) by xylanase supplementation. The lack of a pentosan level ∗ xylanase addition interaction was surprising and contradicts Bedford and Classen (1992), who used rye based diets. The negative relationship between the growth of the birds and wheat pentosan content, but not ileal digesta viscosity, in this study suggests that reduction in viscosity was not the underlying mechanism that explains the mode of action by the enzyme.

The determined AMEn of the diets had a similar range to previous reports of wheat-based diets (Gutierrez del Alamo et al., 2008). The lack of relationship

Table 6. Correlation coefficients (calculated after removing enzyme effects) between broiler growth performance, determined metabolizable energy, viscosity and pentosan content of the wheat inbred lines

	FI	*WG*	*FCE*	*vis vivo*	*AMEn*	*KV*	*DV*	*TP*
WG	0.872							
FCE	0.258	0.695						
vis vivo	− 0.125	− 0.108	− 0.099					
AMEn	0.108	− 0.189	− 0.517	− 0.101				
vis cSt	− 0.618	− 0.519	− 0.100	− 0.377	0.101			
vis cP	− 0.228	− 0.096	0.207	0.012	− 0.093	− 0.096		
TP	− 0.729	− 0.853	− 0.576	− 0.306	0.359	0.551	0.303	
WSP	− 0.537	− 0.503	− 0.208	− 0.229	− 0.103	0.904	− 0.256	0.377

FI, WG, FCE and vis vivo are the feed intakes, weight gains, feed conversion efficiencies and digesta viscosity of the birds fed diets containing 650 g/kg of the experimental wheat samples.

AMEn is the determined N corrected dietary apparent metabolizable energy of the experimental wheat samples.

KV, DV, TP and WSP are the determined kinematic water extracted viscosity, dynamic water extracted viscosity, total pentosans and water soluble pentosans of the experimental wheat samples.

Df = 8; Correlation coefficients greater than 0.549, 0.632 and 0.765 are statistically significant at $P < 0.1$, $P < 0.05$ and $P < 0.001$, respectively.

between dietary AMEn and wheat pentosan content in the present experiment was unexpected. Birds do not produce enzymes to hydrolase pentosans, however the gut microflora possess these enzymes and could utilize them as an energy source. However, the energy released may be primarily used for bacterial growth and metabolism in the distal part of the digestive tract, providing little benefit to the host bird.

It has been well documented that metabolizable energy is not a reliable predictor of the feeding quality of wheat for poultry (Pirgozliev et al., 2003; Amerah et al., 2009; Ball et al., 2013), thus the lack of relationships between dietary AMEn and the birds' growth performances is not a surprise. This study clearly showed a negative relationship between pentosan content and the weight gain and feed intake of the broiler chickens. This information indicates that it is beneficial to reduce pentosan levels in wheat varieties selected for poultry feeding.

Supplementary xylanase improved dietary AMEn in accord with Gutierrez del Alamo et al. (2008). The majority of the available energy in wheat grains comes from starch that is stored intracellularly, and is partly inaccessible to poultry as their endogenous ability to degrade plant cell wall material is limited (Masey O'Neill et al., 2014). Thus, supplementation with enzymes capable of degrading cell wall polysaccharides, i.e. xylanases, may allow pancreatic enzymes access to nutrients trapped within the cell and improve dietary metabolizable energy.

The determined kinematic viscosity was positively correlated to total and water soluble pentosans of the wheat samples, but there was no correlation with dynamic viscosity. Dynamic viscosity measures the internal friction of the fluid or the resistance of a fluid to flow under mechanical stress at a given temperature and pressure, whereas the kinematic viscosity measures the resistance of the liquid to flow in the presence of gravity (Julien, 2010). Apart from the gizzard, the gastrointestinal tract of poultry does not have muscles that are sufficiently powerful to exert a high pressure, therefore, KV is more relevant to the conditions in the gut of poultry than DV.

There was also no relationship between *in vivo* viscosity and wheat pentosan content in this experiment. However, all the diets used in this experiment gave a low *in vivo* viscosity.

In conclusion, this study shows that the growth performance of broiler chickens fed different wheat samples is negatively correlated to their total pentosan content in a linear fashion. This information may be of practical importance to plant breeders who may be able to incorporate reduced total pentosan content in the development of new feed wheat cultivars.

REFERENCES

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

Annison, G. 1991. Relationship between the levels of non-starch polysaccharides and apparent metabolisable energy of wheat assayed in broiler chickens. J. Agric. Food Chem. 39: 1252–1256.

Association of Official Analytical Chemists. 2000. Official Methods of Analysis. 17th ed. AOAC, Gaithersburg, MD.

Ball, M. E. E., B. Owens, and K. J. McCracken. 2013. Chemical and Physical Predictors of the Nutritive Value of Wheat in Broiler Diets. Asian Australas. J. Anim. Sci. 26:97–107.

Bedford, M. R., and H. L Classen. 1992. Reduction of intestinal viscosity through manipulation of dietary rye and pentosanase concentration is effected through changes in the carbohydrate composition of the intestinal aqueous phase and results in improved growth rate and food conversion efficiency of broiler chicks. J. Nutr. 122:560–569.

Carré, B., A. Idi, S. Maisonnier, J.-P. Melcion, F.-X. Oury, J. Gomez, and P. Pluchard. 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.

Choct, M., and G. Annison. 1990. Anti-nutritive activity of wheat pentosans in broiler diets. Br Poult Sci. 31:811–821.

Choct, M., and G. Annison. 1992. Anti-nutritive activity of the wheat pentosans in broiler chicken: role of viscosity and gut microflora. Br. Poult. Sci. 33:821–834.

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

Choct, M., R. J. Hughes, and M. R. Bedford. 1999. Effect of a xylanase on individual bird variation, starch digestion throughout the intestine, and ileal and caecal volatile fatty acid production in chickens fed wheat. Br Poult Sci. 40:419–422.

Douglas, S. G. 1981. A rapid method for the determination of pentosans in wheat flour. Food Chem. 7:139–145.

Finnie, S. M., A. D. Bettge, and C. F. Morris. 2006. Influence of cultivar and environment on water-soluble and water-insoluble arabinoxylans in soft wheat. Cereal Chem. 83:617–623.

Jourdian, G. W., L. Dean, and S. Roseman. 1971. A periodate- resorcinol method for the quantitative estimation of free sialic acids and their glycosides. J. Biol. Chem. 246:430–435.

Julien, P. Y. 2010. Erosion and sedimentation, 2nd ed., Cambridge University Press, Cambridge.

International Grains Council. 2013. World grain statistics. International Grains Council, London.

Hill, F. W., and D. L. Anderson. 1958. Comparison of metabolisable energy and productive energy determinations with growing chicks. J. Nutr. 64:587–603.

Gebruers, K., E. Dornez, D. Boros, A. Fras, W. Dynkowska, Z. Bedo, M. Rakszegi, J. A. Delcour, and C. M. Courtin. 2008. Variation in the content of dietary fiber and components thereof in wheats in the HEALTHGRAIN diversity screen. J. Agric. Food Chem. 56:9740–9749.

Gutiérrez-Alamo, A., P. Pérez de Ayala, M. W. A. Verstegen, L. A. Den Hartog, and M. J. Villamide. 2008. Variability in wheat: factors affecting its nutritional value. Worlds Poult Sci J. 64:20–39.

Gutierrez del Alamo, A., M. W. A. Verstegen, L. A. Den Hartog, P. Perez de Ayala, and M. J. Villamide. 2008. Effect of wheat cultivar and enzyme addition to broiler chicken diets on nutrient digestibility, performance, and apparent metabolizable energy content. Poultry Science 87:759–767.

Kettlewell, P. S., R. B. Sothern, and W. L. Koukkari. 1999. UK wheat quality and economic value are dependent on the North Atlantic Oscillation. J. Cereal Sci. 29:205–209.

Langhout, D. J., J. B. Schutte, J. de Jong, H. Sloetjes, M. W. A. Verstegen, and S. Tamminga. 2000. Effect of viscosity on digestion of nutrients in conventional and germ-free chicks. Br. J. Nutr. 83:533–540.

Masey O'Neill, H. V., J. A. Smith, and M. R. Bedford. 2014. Multicarbohydrase enzymes for non-ruminants. Asian Australas. J. Anim. Sci. 27:290–301.

McCracken, K. J., M. R. Bedford, and R. A. Stewart. 2001. Effects of variety, the 1B/1R translocation and xylanase supplementation on nutritive value of wheat for broilers. Br Poult Sci. 42: 638–642.

Olukosi, O. A., A. J. Cowieson, and O. Adeola. 2007. Age-related influence of a cocktail of xylanase, amylase and protease or phytase individually or in combination in broilers. Poultry Science 86:77–86.

Peng, J. H., D. Sun, and E. Nevo. 2011. Domestication evolution, genetics and genomics in wheat. Molecular Breeding. 28(3):281–301.

Pirgozliev, V. R., C. L. Birch, S. P. Rose, P. S. Kettlewell, and M. R. Bedford. 2003. Chemical composition and the nutritive quality of different wheat cultivars for broiler chickens. Br Poult Sci. 44:464–475.

Porter, J. R., and M. A. Semenov. 2005. Crop responses to climatic variation. Phil. Trans. R. Soc. B 360:2021–2035.

Poutanen, K., R. Shepherd, P. R. Shewry, J. A. Delcour, I. Björck, and J.-W. van der Kamp. 2008. Beyond whole grain: the European HEALTHGRAIN project aims at healthier cereal food. Cereal Foods World 53:32–35.

Rose, S. P., L. A. Tucker, P. S. Kettlewell, and J. D. A. Collier. 2001. Rapid tests of wheat nutritive value for growing chickens. J. Cereal Sci. 34:181–190.

Steenfeldt, S. 2001. The dietary effect of different wheat cultivars for broiler chickens. Br Poult Sci. 42:595–609.

Stone, B., and M. K. Morell. 2009. Carbohydrates. Pages 299–362 in Wheat: Chemistry and Technology, 4th ed. K. Khan, and P. R. Shewry, ed. American Association of Cereal Chemists, St Paul, MN.

Wiseman, J., and J. Inborr. 1990. The nutritive value of wheat and its effect on broiler performance. Pages 79—102 in Recent Advances in Animal Nutrition. W. Haresine, and D. J. A. Cole, ed. Butterworths, London.