



## Chemical and Physical Predictors of the Nutritive Value of Wheat in Broiler Diets

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**ABSTRACT:** The aim of this study was to establish relationships between chemical and physical parameters of wheat with performance and digestibilities of feed components in broiler chickens fed on wheat-based diets. Ninety-four wheat samples were selected for inclusion in four bird trials. Birds were housed in individual wire metabolism cages from 7 to 28 d and offered water and feed *ad libitum*. Dry matter intake (DMI), liveweight gain (LWG) and gain:feed were measured weekly. A balance collection was carried out from 14 to 21 d for determination of apparent metabolizable energy (AME), ME:gain, dry matter retention, oil and neutral detergent fibre (NDF) digestibility. At 28 d the birds were humanely killed, the contents of the jejunum removed for determination of *in vivo* viscosity and the contents of the ileum removed for determination of ileal dry matter, starch and protein digestibility. When wheat parameters were correlated with bird performance data, it was found that specific weight was not significantly ( $p > 0.05$ ) related to bird performance. Bird DMI, LWG and gain:feed were best correlated ( $p < 0.05$ ) with the rate of starch digestion, although the coefficients of correlation ( $r$ ) were still low (0.246 to 0.523). A negative relationship ( $p < 0.01$ ) between AME and total ( $r = -0.432$ ) and soluble ( $r = -0.304$ ) non starch polysaccharide (NSP) was observed in this study. Thousand grain weight (TG) was positively correlated with DMI ( $r = 0.299$ ), LWG ( $r = 0.343$ ) and gain:feed ( $r = 0.371$ ). When establishing multiple regression relationships, correlation coefficients greater than 0.8 were achieved for DMI, LWG, gain:feed and ileal crude protein digestibility. However, the economics involved in determining the parameters involved in the regressions make the process impractical. (**Key Words:** Wheat, Broilers Nutritive Value)

### INTRODUCTION

In Europe, wheat constitutes 60% or more of poultry diets (Austin et al., 1999), supplying 80% of metabolizable energy and 40% of amino acid requirements (McNab, 1991). However, the nutritive value of wheat is variable both in terms of its chemical composition and the availability of energy (Mollah et al., 1983; Rogel et al., 1987). A range of more than 10% in chicken growth rates has been observed when birds are offered different wheat samples (March and Biely, 1973; Rose et al., 1993; Scott et al., 1998; McCracken and Quintin, 2000). Therefore knowledge of the nutritive value of wheat is imperative to the poultry industry. Internationally, specific weight is used as a measure of feed wheat quality, with an agreed arbitrary minimum of 72 kg/hectolitre. However, reports from literature show a lack of relationship between specific weight and nutritive value of wheat for poultry (Wiseman, 2000; Miller et al., 2001;

McCracken et al., 2002).

Other chemical and physical parameters of wheat have been suggested as indicators of feed wheat quality. Wiseman and McNab (1995) reported significant positive correlations between apparent metabolizable energy (AME) of wheat and thousand grain weight (TG) and Pirgozliev et al. (2003) found that TG was negatively correlated with feed conversion efficiency. In contrast, other authors (Hughes et al., 1996; Garnsworthy et al., 2000) found that TG was not correlated with AME. In some studies wheat endosperm hardness was positively correlated with broiler chick growth performance (Scott et al., 1998; Rose et al., 2001; Pirgozliev et al., 2003). Wheat endosperm hardness is an important characteristic in the quality of wheat for bread making (Ohm et al., 1998). Hardness of the endosperm affects the milling performance of wheat. Hard wheats shatter when milled and the flour is fine, with regular particle sizes and large surface areas and they yield angular endosperm particles in which starch granules are often mechanically damaged. Soft wheats tend to result in flour with irregular particle sizes, lower surface areas and with

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relatively little starch granule damage. It has been suggested that these starch damage characteristics may be important in improving the growth performance of broiler chickens fed wheat-based diets (Pirgozliev et al., 2003). However, other studies found that hardness showed no correlation with nutritive value (Garnsworthy et al., 2000).

The nutritive value of any feedstuff is influenced by its chemical composition and the degree to which the bird is able to digest, absorb and utilize these components (Wiseman and Inbarr, 1990). Pirgozliev et al. (2003) showed, by step-wise multiple regression, that the amount of total starch, crude protein and ether extract were the nutrient composition variables significantly related to AME of the diets. Starch is the main source (>50%) of energy in most poultry diets, so variations in starch content and digestibility may strongly affect the energy value of poultry diets (Carré, 2004). McCracken and Quintin (2000) found a strong relationship ( $p < 0.01$ ) between the AME and the starch content of wheat. Rogel et al. (1987) and Wiseman et al. (2000) have both reported that the AME content of wheat is affected by starch digestibility and studies by Weurding (2002) have shown that rapid starch digestion has a negative effect on feed conversion efficiency. Slowly digestible starch is said to improve the efficiency of digestion of protein and amino acids. The rate of starch digestion may also affect the composition of the microflora. Birds fed slowly degradable starch showed a different profile of microflora, less *Clostridium Perfringens* (which is associated with necrotic enteritis) and a trend towards more favourable *Lactobacilli* bacteria, when compared with birds fed faster digested starch ([www.aviagen.com](http://www.aviagen.com)). There is evidence that the endosperm structure of cereals may also affect their nutritive quality. It is generally believed that starch granules, with high amylose content (>40%), tend to be more resistant to enzyme hydrolysis than those with low amylose content. High amylose starch granules (about 70% amylose) from mutant plant genotypes display different crystalline structure, high resistance and low *in vivo* digestibility (Carré, 2004). Very low amylose (<1%) starch granules were also tested in chickens, and despite the fact that the low amylose starch seems more susceptible to enzyme hydrolysis than normal starch (Rooney and Pflugfelder, 1986), there was no clear advantage to low amylose wheat instead of normal wheat cultivars (Weurding et al., 2001; Pirgozliev et al., 2002).

In relation to defining quality, research has also indicated that the content of non-starch polysaccharides (NSP) is responsible for the low AME of some wheats (Annisson, 1990; Classen et al., 1995; Choct et al., 1999). Reportedly, the anti-nutritional effects of NSP in broiler chickens are caused by soluble NSP (mainly arabinoxylan and some  $\beta$ -glucan) present in wheat cell walls. Evidence for the anti-nutritive effect of soluble NSP includes the

negative relationship with AME, the fact that various sources of purified NSP depress AME, and that *in situ* degradation of cell wall NSP by glycanases increases AME (Hughes and Choct, 1999). In Canada, Classen et al. (1995) found a negative relationship between AME and different soluble NSP parameters. The anti-nutritive effect of soluble NSP on AME is manifested through inhibition of digestion of starch, lipid and protein in the small intestine (Choct and Annison, 1992). The mechanism of action of soluble NSP is thought to involve increased viscosity of digesta which limits contact between digestive enzymes and substrates, and contact between nutrients and absorption sites on the intestinal mucosa (Bedford and Morgan, 1996; Smits et al., 1997). Hence, previous studies (Classen and Scott, 1995; Wiseman and McNab, 1995; Dusel et al., 1997) have suggested that *in vitro* viscosity may also be a suitable basis for rapid estimation of energy value. It has been demonstrated that a significant negative relationship exists between intestinal viscosity and weight gain and feed conversion efficiency in chickens fed rye- and wheat-based diets (Bedford et al., 1991; Bedford and Classen, 1992). However, McCracken et al. (2001) found there were poor relationships between either gain:feed or wheat AME and *in vitro* or *in vivo* viscosity. Studies by George (2000) suggested that a considerable component of viscosity of wheat samples was associated with the protein fraction and Chesson et al. (2002) has highlighted the importance of amino acid digestibility of cereals as a component of nutritive value. Although the protein content of cereals is relatively low, the large amounts of cereals in poultry diets means they commonly supply over half of the total dietary protein and any improvements in the digestibility of protein has an important effect on the utilization of the whole diet. Therefore, the protein component of the wheat should also be examined when defining nutritive value.

Considering the range of different parameters suggested and the difference in findings, clarification on the chemical and/or physical factors related to wheat nutritive value is critical. The aims of this project were to identify chemical and physical parameters which consistently relate to the nutritive value of wheats in diets for poultry and to establish regression relationships between bird performance parameters and wheat chemical and physical parameters.

## MATERIALS AND METHODS

### Animal ethics

This study was conducted according to the Animals (Scientific Procedures) Act 1986 and was approved by the Newforge Ethical Committee.

### Sample collection

The 94 wheat samples used in this study were gathered

over a wide range of different locations, varieties and years. Thirty-two of the wheat samples were taken from Miller et al. (2001) and consisted of eight 1999 Northern Ireland varieties (Aardvark, Charger, Hereward, Reaper, Equinox, Napier, Rialto, Savannah and Consort) from two sites (Downpatrick and Limavady) and 16 GB wheats, of four different varieties (Buster, Consort, Riband and Haven) at four levels of specific weight (Broiler trial 1). In addition to these, ten samples: Claire, Consort, Malacca, Tanker, Napier, Savannah, Aarvark, Rialto, Riband and Soissons; were collected from each of the 2003 and 2004 harvests at Crossnacreevy, Northern Ireland (Broiler trial 2). Another 32 samples were collected from the 2005 harvest at Crossnacreevy (n = 10) and from HGCA Project No. 2979 entitled "GREEN Grain" being undertaken by ADAS (n = 18) and also from shipments from GB containing commercial wheat samples for Moy Park Limited (Dungannon, Northern Ireland) (n = 4) (Broiler trial 3). A further ten samples were selected from 2005 Crossnacreevy grain (n = 6) and from the ADAS grain (n = 4) for use in a fourth broiler trial (Broiler trial 4).

## Diets

Wheats were selected to give as wide a range of bird performance results as possible. Wheat was ground in a hammer-mill using a 5 mm screen. The diet formulation (Table 1) was a typical UK starter/grower with a small

**Table 1.** Composition of diets

Component	g/kg
Wheat	650
Soyabean meal	200.5
Full fat soya	40
Fish meal	40
Soya/tallow blend	25
Limestone	8
Dicalcium phosphate	14
Trace minerals/ vitamins*	5
Sodium bicarbonate	2
Salt	2
Choline chloride	0.5
Lysine**	2.5
Methionine**	4.7
Threonine**	2.8
Maize starch**	3.0

\* The trace mineral/vitamin mixture supplied (per kg feed): retinol 3.6 mg, cholecalciferol 0.125 mg,  $\alpha$ -tocopherol 50 mg, thiamine 2 mg, riboflavin 7 mg, vitamin K 3 mg, pyridoxine 5 mg, nicotinic acid 50 mg, calcium pantothenate 15 mg, folic acid 1 mg, biotin 0.2 mg, cobalamin 15  $\mu$ g, manganese 100 mg, iron 80 mg, zinc 80 mg, copper 10 mg, iodine 1 mg, cobalt 0.5 mg, selenium 0.2 mg, molybdenum 0.5 mg.

\*\* For each wheat sample inclusions of lysine, methionine, threonine and maize starch were adjusted on the basis of the determined amino acid analysis of the wheat to equalise total concentrations across all diets.

inclusion of lysine, threonine and methionine to equalize these across all diets based on amino acid analysis of the wheat samples. Titanium dioxide was added as an indigestible marker. The diets were mixed, then heat treated (80°C, 90 s) and pelleted (3 mm die) at the Agri-Food and Biosciences Institute, Belfast.

## Experimental design

The first broiler trial was conducted as part of the study by Miller et al. (2001), which investigated the 16 1999 Northern Ireland varieties and 16 GB wheats. Sixty-four birds were used in each of five replicates (ten birds/treatment), with two weight blocks of 32 in each replicate. All 32 treatments were randomly allocated within a weight block of 32 birds. The second broiler trial investigated 20 wheat samples, ten from each of the 2003 and 2004 Crossnacreevy harvest. Sixty birds were used in each of three replicates (nine birds/treatment), with three weight blocks of 20 in each replicate. All 20 treatments were randomly allocated within a weight block of 20 birds. The third broiler trial investigated 32 wheat samples selected from the 2005 Crossnacreevy harvest, HGCA Project 2979 and GB commercial samples. Sixty-four birds were used in each of five replicates (ten birds/treatment), with two weight blocks of 32 in each replicate. All 32 treatments were randomly allocated within a weight block of 32 birds. The fourth trial investigated ten wheat samples selected from the 2005 Crossnacreevy harvest and HGCA Project No. 2979. Sixty birds were used in each of two replicates (12 birds/treatment), with six weight blocks of ten in each replicate. All ten treatments were randomly allocated within a weight block of ten birds.

## Birds and management

For each replicate, 100 male Ross broiler chicks from 30 to 40 wk old breeders and one breeder farm were obtained at hatching from Moy Park Ltd. (Dungannon, Northern Ireland). They were placed in a commercial brooder for seven days with *ad libitum* access to water and a crumbled starter diet (Hi-Grain Chick Crumbs, John Thompson and Sons, Belfast, UK). This contained cereal grains, oilseed products and by-products, cereal grain products and by-products, minerals, oils and fats. Proximate analysis (g/kg) of the commercial starter diet (as given by the supplier) gave oil 35, protein 195, fibre 40, ash 60 and methionine 4. At seven days, all birds were weighed and the heaviest and lightest discarded, leaving a sufficient amount so the birds can be allocated to experiment according to the randomization. Birds were placed in individual wire metabolism cages (31×22.5×30 cm<sup>3</sup>) at an initial room temperature of 33°C, reduced by 1°C every two days down to 24°C. The light:dark cycle was 18:6 and relative humidity was set for 50%. Birds were offered water and

feed *ad libitum* from 7 to 28 d, with DMI, LWG and gain:feed being recorded on a weekly basis.

The balance procedure for determination of AME was carried out from d 14 to d 21. The individual bird excreta was collected daily and stored at 4°C. At the end of the balance week the excreta was weighed and then oven dried at 80°C. The sample weights were allowed to equilibrate and were then milled through a hammer mill fitted with a 0.75 mm screen and stored for subsequent analysis. At 28 d, birds were humanely killed by dislocation of the spinal cord and the contents of the proximal jejunal removed for determination of *in vivo* viscosity and the contents of the ileum collected to determine ileal digestibility.

#### Analysis of wheat samples, diets, excreta and ileal digesta

The wheat samples were analyzed for DM, specific weight, TG, *in vitro* viscosity, gross energy (GE), nitrogen (N), neutral detergent fibre (NDF), starch, total and soluble NSP, lysine, threonine, amylose, hardness, rate of starch digestion and protein profiles. The diets were analyzed for titanium dioxide, DM, crude protein (N×6.25), oil, NDF, ash, starch and GE. The excreta samples were analyzed for DM, GE, oil and NDF content. The ileal digesta were analyzed for DM, titanium dioxide, crude protein (N×6.25) and starch. All analyses were carried out in duplicate and results reported on a DM basis.

DM was determined by oven drying at 100°C for 24 h and ash content was determined by ashing samples in a muffle furnace at 450°C for 16 h (AOAC, 1990). Specific weight was measured using a Digi-sampler hectolitre test weight machine (ELE International Limited), and TG by using a Numigral seed counter (Tecator Ltd, Sweden) and measuring the weight of one thousand grains in duplicate. *In vitro* viscosity was determined using a modification of the method described by Bedford and Classen (1993). The digesta was centrifuged (13,400 g for 8 min) and viscosity measured using a Brookfield LVDV II cone and plate viscometer at 20°C. Nitrogen was determined using the LECO FP-2000 dry combustion analyzer (Leco Corporation, Michigan, USA) and oil B by acid hydrolysis (3 M-HCl), followed by solvent extraction with petroleum ether (40 to 60°C) in a Soxtec system (Stoldt, 1952). NDF was determined using the Fibertec system (Tecator Ltd, UK) according to the method of Van Soest (1963) and total starch was determined using a commercial enzyme assay kit (Megazyme International Ireland Ltd) as described by McCleary et al. (1997). Total and soluble NSP content were determined using a commercial enzyme assay kit as described by Englyst et al. (1994). Amino acid content was determined, following acid hydrolysis (6 N HCl), on a Biochrom 20 amino acid analyzer, using the synthetic

amino acid Norleucine as an internal standard. GE was determined using an isothermal automated bomb calorimeter (PARR, Model 1271). Amylose content was determined using a commercial assay kit (Megazyme International Ireland Limited) which is a modification of the procedure as described by Yun and Matheson (1990). The hardness of the wheat samples was firstly measured using NIRS to predict a single kernel characterization system (SKCS) (Harper Adams University) and then repeated at AFBI, Hillsborough using a more recent version of the equation obtained from Campden Chorleywood Food Research Association (CCFRA, Gloucestershire). Rate of starch digestion was determined by the Englyst method (Englyst et al., 1996). *In vitro* starch digestion follows first-order kinetics, and *in vitro* starch digestion rate was estimated using the following equation:  $DC_t = D(1 - e^{-k_d t})$ , where  $DC_t$  is the starch fraction at time  $t$  and fraction  $D$  is the potentially digestible starch fraction that will digest at a fractional rate of  $k_d$  ( $h^{-1}$ ). This terminology was the same as used by Weurding et al. (2001). The percentage starch at each time period was expressed as a fraction of the final starch value obtained from the above rate equation. Profiling of the protein fractions was measured by electrophoretic and densitometric analysis and this was carried out by CCFRA, Gloucestershire. The detected bands were grouped into five major bands: band 1: HMW-glutenin subunits, band 2: larger LMW-glutenin and  $\omega$ -gliadin subunits, band 3: smaller LMW-glutenin and  $\omega$ -gliadin subunits, band 4:  $\alpha$ -,  $\beta$ -,  $\gamma$ -gliadin subunits and band 5: albumins and globulins. Titanium dioxide content was measured according to the procedure by Leone (1973) and modified by Peddie et al. (1982).

#### Statistical analysis

The results of the trials were subjected to analysis of variance using Genstat Release 9.2, with initial weight as a co-variate for growth parameters. Regression relationships between all bird performance parameters and all wheat chemical and physical parameters were established and a number of multiple regressions examined using stepwise regressions. For the stepwise regressions, forwards selection was used with additional explanatory variates added until no significant improvement in fit was obtained.

## RESULTS

Table 2 shows the range and standard deviation of chemical and physical parameters of wheat. The range in broiler performance and the nutrient utilization of the wheats when formulated into diets is given in Table 3.

#### Regression analysis

All results from the single regression analysis are shown

**Table 2.** The range and standard deviation of chemical and physical parameter of wheat

	Minimum	Mean	Maximum	Standard deviation
Specific weight (kg/hl)	60.0	71.3	78.0	3.99
Thousand grain weight (g)	28.7	45.6	60.8	7.85
<i>In vitro</i> viscosity (cp)	4.3	12.4	44.0	6.87
Nitrogen (g/kg DM)	12.5	18.8	24.0	2.57
Neutral detergent fibre (g/kg DM)	101.3	139.6	178.6	13.13
Starch (g/kg DM)	567.0	644.2	719.0	31.72
Total non starch polysaccharide (g/kg DM)	81.7	108.3	138.8	12.13
Soluble non starch polysaccharide (g/kg DM)	8.4	23.6	38.0	5.95
Gross energy (MJ/kg DM)	18.1	18.4	18.7	0.12
Amylose (g/kg DM)	115.0	159.2	182.3	11.77
Lysine (g/kg DM)	1.8	3.5	5.6	0.61
Threonine (g/kg DM)	1.2	3.4	4.9	0.80
Hardness (%)	8.4	31.4	55.5	11.80
Rate of starch digestion constant	1.3	2.5	4.4	0.60
Protein profile - Band 1	2.1	5.0	7.9	1.08
Protein profile - Band 2	9.1	14.5	18.8	2.06
Protein profile - Band 3	10.2	18.4	23.6	3.47
Protein profile - Band 4	24.3	35.4	48.1	4.43
Protein profile - Band 5	20.9	26.6	37.4	3.30

in Table 4(a), (b) and Table 5. Total DMI, LWG and gain:feed were positively correlated with TG, *in vitro* viscosity, total NSP (DMI and LWG only), soluble NSP (DMI only), threonine, hardness, RSD rate constant and protein band 4 ( $\alpha$ -,  $\beta$ -,  $\gamma$ -gliadin subunits), and negatively correlated with lysine, protein band 1 (HMW-glutenin

subunits) and 2 (larger LMW-glutenin and  $\omega$ -gliadin subunits). *In vivo* viscosity was positively correlated with *in vitro* viscosity, NDF, hardness, protein band 2 and protein band 5 (albumins and globulins) and negatively correlated with starch, amylose and protein bands 3 (smaller LMW-glutenin and  $\omega$ -gliadin subunits) and 4. ME:GE, AME

**Table 3.** The range and standard deviation in broiler performance and nutrient utilisation

	Minimum	Mean	Maximum	Standard deviation
Dry matter intake (g/d)				
7-14 d	28.8	34.4	39.3	2.40
14-21 d	58.6	71.5	83.1	4.73
21-28 d	92.2	115.2	134.9	8.84
Total	61.6	73.8	85.7	4.94
Liveweight gain (g/d)				
7-14 d	21.4	28.5	33.2	3.34
14-21 d	42.4	57.5	65.1	5.90
21-28 d	58.1	81.8	96.3	8.45
Total	41.9	55.9	64.2	5.67
Gain:feed				
7-14 d	0.731	0.828	0.906	0.051
14-21 d	0.719	0.804	0.884	0.044
21-28 d	0.615	0.711	0.782	0.032
Total	0.672	0.758	0.817	0.036
<i>In vivo</i> viscosity (cp)	3.3	5.9	13.0	1.97
Apparent metabolizable energy (MJ/kg DM)	12.7	13.9	14.7	0.44
ME:gain	16.5	18.3	20.7	0.89
Dry matter retention	0.697	0.721	0.753	0.013
Ileal dry matter digestibility	0.627	0.700	0.756	0.027
Ileal starch digestibility	0.832	0.917	0.972	0.033
Ileal crude protein digestibility	0.703	0.769	0.832	0.033

**Table 4. a)** Relationships between bird parameters and chemical and physical parameters of wheat

Parameter	Correlation coefficient						
	Dry matter intake	Liveweight gain	Gain:feed	<i>In vivo</i> viscosity	ME:GE*	AME**	ME:Gain
Specific weight	0.031	0.008	-0.019	0.057	0.118	0.114	0.086
Thousand grain weight	<b>0.299</b>	<b>0.360</b>	<b>0.371</b>	-0.112	0.019	0.057	<b>-0.260</b>
<i>In vitro</i> viscosity	<b>0.371</b>	<b>0.343</b>	<b>0.224</b>	<b>0.306</b>	<b>-0.254</b>	<b>-0.216</b>	<b>-0.333</b>
Crude protein	0.079	0.106	0.135	-0.073	<b>-0.374</b>	<b>-0.344</b>	<b>-0.283</b>
Neutral detergent fibre	-1.033	-0.046	0.037	<b>0.530</b>	<b>0.203</b>	<b>0.233</b>	0.036
Starch	0.183	0.013	<b>-0.199</b>	<b>-0.399</b>	<b>-0.407</b>	<b>-0.446</b>	-0.087
Total non starch polysaccharides	<b>0.395</b>	<b>0.312</b>	0.148	0.150	<b>-0.485</b>	<b>-0.445</b>	<b>-0.429</b>
Soluble non starch polysaccharides	<b>0.232</b>	0.136	-0.017	0.152	<b>-0.370</b>	<b>-0.334</b>	<b>-0.252</b>
Lysine	<b>-0.494</b>	<b>-0.469</b>	<b>-0.327</b>	0.152	0.027	-0.004	<b>0.314</b>
Threonine	<b>0.307</b>	<b>0.292</b>	<b>0.211</b>	-0.007	<b>-0.272</b>	<b>-0.238</b>	<b>-0.384</b>
Gross energy	0.111	0.110	0.105	0.064	<b>-0.403</b>	<b>-0.349</b>	<b>-0.299</b>
Amylose	0.017	0.007	-0.011	<b>-0.516</b>	-0.066	-0.089	-0.032
Hardness	<b>0.385</b>	<b>0.409</b>	<b>0.385</b>	<b>0.203</b>	-0.058	-0.068	<b>-0.305</b>
RSD rate constant	<b>0.508</b>	<b>0.459</b>	<b>0.304</b>	0.043	<b>-0.342</b>	<b>-0.281</b>	<b>-0.449</b>
Protein profile - Band 1	<b>-0.268</b>	<b>-0.282</b>	<b>-0.233</b>	-0.091	0.029	-0.016	0.149
Protein profile - Band 2	<b>-0.382</b>	<b>-0.317</b>	<b>-0.181</b>	<b>0.332</b>	<b>0.413</b>	<b>0.357</b>	<b>0.296</b>
Protein profile - Band 3	-0.128	-0.126	-0.098	<b>-0.326</b>	-0.022	-0.022	0.129
Protein profile - Band 4	<b>0.405</b>	<b>0.363</b>	<b>0.252</b>	<b>-0.510</b>	<b>-0.401</b>	<b>-0.376</b>	<b>-0.408</b>
Protein profile - Band 5	-0.083	-0.068	-0.053	<b>0.364</b>	<b>0.286</b>	<b>0.300</b>	<b>0.178</b>

Correlation values  $\geq 0.173$ , 0.242, 0.318 are significant ( $p < 0.05$ , 0.01 and 0.001 respectively). Significant correlations are highlighted in bold.

\* ME:GE = Metabolizable energy:gross energy. \*\* AME = Apparent metabolizable energy.

content and ME:gain were positively correlated with NDF (AME and ME:GE only), protein band 2 and protein band 5 (ME:GE and AME only) and negatively correlated with *in vitro* viscosity, CP, starch (ME:GE and AME only), total NSP, soluble NSP, threonine, GE, RSD rate constant hardness (ME:gain only) and protein band 4. DM retention was positively correlated with starch and threonine and negatively correlated with *in vitro* viscosity, CP, total NSP,

**Table 4. b)** Relationships between bird digestibility parameters and chemical and physical parameters of wheat

Parameter	Correlation coefficient			
	DM retention	Ileal DM digestibility	Ileal starch digestibility	Ileal CP digestibility
Specific weight	-0.017	-0.001	-0.100	0.167
Thousand grain weight	-0.052	<b>0.249</b>	<b>-0.238</b>	<b>0.357</b>
<i>In vitro</i> viscosity	<b>-0.181</b>	-0.124	<b>-0.529</b>	<b>0.387</b>
Crude protein	<b>-0.269</b>	<b>-0.209</b>	<b>-0.298</b>	<b>0.259</b>
Neutral detergent fibre	-0.151	<b>-0.165</b>	<b>-0.311</b>	<b>0.279</b>
Starch	<b>0.270</b>	0.145	<b>0.594</b>	<b>-0.513</b>
Total non starch polysaccharides	<b>-0.208</b>	<b>-0.178</b>	<b>-0.405</b>	<b>0.361</b>
Soluble non starch polysaccharides	-0.156	-0.157	<b>-0.206</b>	0.128
Lysine	<b>-0.225</b>	-0.074	0.098	-0.089
Threonine	<b>0.176</b>	<b>-0.426</b>	<b>-0.425</b>	-0.014
Gross energy	<b>-0.325</b>	-0.136	<b>-0.211</b>	0.282
Amylose	-0.035	0.089	<b>0.296</b>	<b>-0.348</b>
Hardness	-0.088	-0.160	<b>-0.396</b>	<b>0.337</b>
RSD rate constant	0.021	-0.163	<b>-0.506</b>	<b>0.389</b>
Protein profile - Band 1	-0.126	<b>-0.197</b>	0.067	<b>-0.217</b>
Protein profile - Band 2	<b>-0.320</b>	<b>-0.189</b>	-0.014	-0.102
Protein profile - Band 3	0.050	0.139	<b>0.385</b>	<b>-0.325</b>
Protein profile - Band 4	-0.059	<b>-0.187</b>	<b>-0.496</b>	<b>0.420</b>
Protein profile - Band 5	0.020	<b>0.217</b>	0.130	0.003

Correlation values  $\geq 0.173$ , 0.242, 0.318 are significant ( $p < 0.05$ , 0.01 and 0.001 respectively). Significant correlations are highlighted in bold.

lysine, GE and protein band 2 (Table 4). Ileal dry matter digestibility was positively correlated with TG and was negatively correlated with CP, total NSP, threonine and protein bands 1, 2, 4 and 5. Ileal starch digestibility was positively correlated with starch, amylose and protein band 3 and negatively correlated with TG *in vitro* viscosity, NDF, CP, total NSP, soluble NSP, threonine, GE, hardness, RSD rate constant and protein band 4. Ileal CP digestibility tended to show opposite correlations to those of ileal starch digestibility, with ileal CP being positively correlated with TG, *in vitro* viscosity, CP, NDF, total NSP, GE, hardness, RSD rate constant and protein band 4 and negatively correlated with starch, amylose and protein bands 1 and 3. A number of significant correlations were observed between wheat chemical and physical parameters (Table 5). Specific weight was positively correlated with hardness and protein bands 1 to 3 but negatively correlated with CP, total NSP, soluble NSP, threonine and protein band 4. Thousand grain weight was positively correlated with *in vitro* viscosity, amylose, RSD rate constant and protein band 4 and negatively correlated with lysine and protein bands 1 to 3. *In vitro* viscosity was positively correlated with CP, total NSP, soluble NSP, threonine, GE, hardness, RSD rate constant and protein band 3 and was negatively correlated with starch, amylose and protein bands 1 and 3. CP was positively correlated with total NSP, soluble NSP, lysine, threonine, GE, hardness, RSD rate constant and protein bands 1 and 4 and was negatively correlated with starch, amylose and protein band 5. NDF was positively correlated

with total NSP, lysine, GE, hardness and protein band 2 and was negatively correlated with starch, amylose and protein band 3. Starch was positively correlated with amylose and was negatively correlated with lysine, GE, hardness and protein band 2. Total NSP was positively correlated with soluble NSP, threonine, GE, hardness, RSD rate constant and protein band 4 and negatively correlated with amylose and protein bands 1 and 3. Soluble NSP was positively correlated with threonine, GE, hardness, RSD rate constant and protein bands 4 and 5 and negatively correlated with amylose and protein bands 1 to 3. Lysine was positively correlated with protein bands 1 and 2 and negatively correlated with threonine and amylose. Threonine was positively correlated with GE, hardness, RSD rate constant and protein band 4 and negatively correlated with protein bands 2 and 3. GE was positively correlated with hardness, RSD rate constant and protein bands 1 and 4 and negatively correlated with amylose. Amylose was positively correlated with protein bands 1 and 3 and negatively correlated with hardness, RSD rate constant and protein band 2. Hardness was positively correlated with RSD rate constant and protein band 4 and negatively correlated with protein band 3. RSD rate constant was positively correlated with protein band 4 and negatively correlated with protein bands 2, 3 and 5. Protein band 1 was positively correlated with protein bands 1 and 2 and negatively correlated with protein band 5. Protein band 2 was negatively correlated with protein band 4. Protein band 3 was negatively correlated with protein band 4 and 5 and protein band 4 was negatively correlated

**Table 5.** Correlation between chemical and physical parameters of wheat

	Specific weight	Thousand grain weight	<i>In vitro</i> viscosity	Crude protein	Neutral detergent fibre	Starch	Total NSP	Sol NSP	Lysine	Threonine	Gross energy	Amylose	Hardness	RSD rate constant	Protein profile band 1	Protein profile band 2	Protein profile band 3	Protein profile band 4	
Specific weight	0.057																		
Thousand grain Weight		0.057																	
<i>In vitro</i> viscosity	-0.027	<b>0.175</b>																	
Crude protein	<b>-0.206</b>	-0.047	<b>0.226</b>																
Neutral detergent fibre	0.011	0.011	0.058	0.152															
Starch	-0.137	0.058	<b>-0.209</b>	<b>-0.241</b>	<b>-0.606</b>														
Total non starch polysaccharides	<b>-0.227</b>	0.130	<b>0.398</b>	<b>0.360</b>	<b>0.275</b>	-0.006													
Soluble non starch polysaccharides	<b>-0.280</b>	0.143	<b>0.382</b>	<b>0.244</b>	0.149	-0.009	<b>0.649</b>												
Lysine	-0.168	<b>-0.336</b>	-0.073	<b>0.197</b>	<b>0.189</b>	<b>-0.249</b>	0.045	-0.040											
Threonine	<b>-0.305</b>	0.070	<b>0.281</b>	<b>0.507</b>	-0.101	0.053	<b>0.301</b>	<b>0.276</b>	<b>-0.255</b>										
Gross energy	0.043	-0.129	<b>-0.259</b>	<b>0.808</b>	<b>0.264</b>	<b>-0.243</b>	<b>0.317</b>	<b>0.262</b>	0.142	<b>0.332</b>									
Amylose	0.075	<b>0.286</b>	<b>-0.280</b>	<b>-0.178</b>	<b>-0.559</b>	<b>0.404</b>	<b>-0.353</b>	<b>-0.189</b>	<b>-0.210</b>	-0.072	<b>-0.208</b>								
Hardness	<b>0.330</b>	-0.121	<b>0.665</b>	<b>0.262</b>	<b>0.406</b>	<b>-0.647</b>	<b>0.567</b>	<b>0.405</b>	-0.151	<b>0.280</b>	<b>0.211</b>	<b>-0.375</b>							
RSD rate constant	-0.065	<b>0.227</b>	<b>0.389</b>	<b>0.387</b>	0.075	-0.119	<b>0.642</b>	<b>0.411</b>	-0.114	<b>0.447</b>	<b>0.291</b>	<b>-0.180</b>	<b>0.745</b>						
Protein profile - Band 1	<b>0.371</b>	<b>-0.242</b>	<b>-0.222</b>	<b>0.268</b>	-0.122	-0.079	<b>-0.274</b>	<b>-0.366</b>	<b>0.267</b>	-0.007	<b>0.215</b>	<b>0.211</b>	-0.162	-0.018					
Protein profile - Band 2	<b>0.277</b>	<b>-0.190</b>	-0.038	-0.170	<b>0.446</b>	<b>-0.518</b>	<b>-0.249</b>	<b>-0.357</b>	<b>0.212</b>	<b>-0.498</b>	-0.103	<b>-0.267</b>	0.016	<b>-0.327</b>	<b>0.178</b>				
Protein profile - Band 3	<b>0.242</b>	<b>-0.368</b>	<b>-0.500</b>	-0.125	<b>-0.282</b>	0.167	<b>-0.536</b>	<b>-0.443</b>	-0.138	<b>-0.279</b>	-0.070	<b>0.292</b>	<b>-0.285</b>	<b>-0.342</b>	<b>0.199</b>	0.002			
Protein profile - Band 4	<b>-0.304</b>	<b>0.425</b>	<b>0.325</b>	<b>0.486</b>	-0.080	0.149	<b>0.641</b>	<b>0.474</b>	0.013	<b>0.540</b>	<b>0.298</b>	-0.055	<b>0.287</b>	<b>0.575</b>	-0.107	<b>-0.412</b>	<b>-0.648</b>		
Protein profile - Band 5	-0.139	0.013	0.148	<b>-0.505</b>	0.164	-0.019	-0.047	<b>0.174</b>	-0.093	-0.121	-0.332	-0.134	0.029	<b>-0.203</b>	<b>-0.506</b>	-0.133	<b>-0.248</b>	<b>-0.366</b>	

Correlation values  $\geq 0.173$ , 0.242, 0.318 are significant ( $p < 0.05$ , 0.01 and 0.001 respectively). Significant correlations are highlighted in bold.

with protein band 5.

The results from the stepwise multi-regression analysis are shown in Table 6. The best prediction combinations were for total DMI ( $r = 0.824$ ,  $p < 0.001$ ) from *in vitro* viscosity, lysine, TG and RSD (2 h); total LWG ( $r = 0.860$ ,  $p < 0.001$ ) from TG, RSD (2 h) lysine, soluble NSP, starch and SW; total gain:feed ( $r = 0.863$ ,  $p < 0.001$ ) from TG, RSD (2 h), soluble NSP, protein band 1, CP and NDF and ileal starch digestibility ( $r = 0.829$ ,  $p < 0.001$ ) from TG, soluble NSP, amylose, RSD (0.125 and 1 h) and starch.

## DISCUSSION

### Characteristics of wheat samples

The wheat samples used in this study were sourced over different locations, years and growing conditions to create a wheat sample database with wide ranging chemical and physical parameters. This aim was successful in that the ranges for each of the measured parameters were greater than most quoted in literature, but still within typical limits expected for wheat (Garnsworthy et al., 2000; McCracken and Quintin, 2000; McCracken et al., 2001; Rose et al., 2001; Steinfeldt, 2001; Carré et al., 2002; Pirgozliev et al., 2003; Wilkinson et al., 2003; Rafuse et al., 2005; Samli et al., 2006).

### Correlations

One of the primary objectives of this study was to

determine the relationship (if any) between wheat chemical and physical parameters and performance variables. The comparison of the results of this study with other results from literature (Garnsworthy et al., 2000; McCracken and Quintin, 2000; McCracken et al., 2001; Rose et al., 2001; Steinfeldt, 2001; Carré et al., 2002; Pirgozliev et al., 2003; Wilkinson et al., 2003; Rafuse et al., 2005) proved difficult as no other study measured the wide range of parameters assessed in this study and of those that had measured the same parameters, the results varied. Therefore, because of the variance of results from the literature and the relatively poor correlations obtained in this study (maximum correlation coefficient ( $r$ ) of 0.594), it is difficult to clearly define which of the wheat properties are most useful, if any, in indicating bird responses. However, specific weight was not significantly ( $p > 0.05$ ) related to any of the bird parameters measured in this study. This agrees with other reports (McCracken et al., 2001; Rose et al., 2001; Pirgozliev et al., 2003), which also show a lack of correlation between wheat specific weight and bird performance parameters. This further enhances the argument that specific weight is of no benefit when predicting feed wheat nutritive value for broilers and use of the industry standard of 72 kg/hl cannot be justified.

Thousand grain weight was positively correlated with DMI ( $r = 0.299$ ), liveweight gain ( $r = 0.343$ ) and gain:feed ( $r = 0.371$ ), which agrees with the findings of previous work (Pirgozliev et al., 2003). However, TG was not related

**Table 6.** Multi-regression analysis

Bird parameter	r	p	Standard error	Best predictor combination*
Dry matter intake (DMI)	0.824	<0.001	3.03	DMI = 32.6 [15.3]+0.2074 [0.0865]-2.667 [0.687] lysine+0.1893 [0.0651] TG+0.361 [0.146] RSD (2 hr value)
Liveweight gain (LWG)	0.860	<0.001	3.64	LWG = 69.8 [40.6]+0.3131 [0.0822]+0.8 [0.202] RSD (2 hr value)-3.822 [0.935] lysine-0.448 [0.140] Sol NSP-0.0821 [0.0314] Starch-0.521 [0.232] SW
Total gain:feed	0.863	<0.001	0.029	Gain:feed = 0.1429 [0.0992]+0.002359 [0.000528] TG+0.0619 [0.00103] RSD (2 hr value)-0.002872 [0.000912] Sol NSP-0.02084 [0.00487] Protein band 1+0.001414 [0.000322]-0.000820 [0.000363] NDF
<i>In vitro</i> viscosity	0.652	<0.001	1.70	<i>In vitro</i> viscosity = -11.01 [3.08]+0.1183 [0.241] Total NSP+0.1919 [0.0781] Protein band 5
Apparent metabolizable energy (AME)	0.358	<0.05	0.266	AME content = 15.153 [0.407]-0.0683 [0.0260] Protein band 2
ME:gain	0.633	<0.001	0.818	ME:gain = 32.94 [3.09]-0.1185 [0.0305] RSD (2 hr value)-0.0461 [0.0157] TG
ME:GE	0.313	<0.05	0.0119	ME:GE = 0.7884 [0.0182]-0.00263 [0.00116] Protein band 2
Ileal DM digestibility	0.554	<0.001	0.019	Ileal DM digestibility = 0.7571 [0.0290]-0.000423 [0.000185] CP -0.0001849 [0.000606] Sol NSP+0.000751 [0.000368] TG
Ileal starch digestibility	0.654	<0.001	0.027	Ileal starch digestibility = 0.554 [0.119]+0.000609 [0.000183] starch-0.001518 [0.000685] <i>in vitro</i> viscosity
Ileal crude protein (CP) digestibility	0.829	<0.001	0.018	Ileal CP digestibility = 1.271 [0.145]+0.001760 [0.000361]-0.003258 [0.000650] Sol NSP-0.000959 [0.000222]+0.002826 [0.000767] RSD (0.125 hr value)-0.002650 [0.000986] RSD (1 hr value)-0.00035 [0.000148] starch

\* Values in [ ] parenthesis = Standard error of each of the multiple regression coefficients.



to AME ( $p > 0.05$ ) and this again is in keeping with previous work from our laboratory (Magee, 1994; McCracken et al., 2001).

In this study, numerous wheat chemical and physical parameters were significantly ( $p < 0.05$ ) related to bird performance. DMI and LWG were best correlated with RSD ( $r = 0.523$  and  $0.50$  respectively) at 0.375 h, and all RSD parameters were positively related ( $p < 0.05$ ) to DMI, LWG and gain:feed. In the current study, the relationships with RSD, although significant, were relatively weak ( $r < 0.523$ ) and significances may be attributed to the large dataset. However, it would appear that the rate of starch digestion plays an important role in bird performance. This agrees with Waldron et al. (1995) who also found increases in hydrolysis of starch were related to increases in weight gain and concluded that the lower rates of starch hydrolysis that occur in some wheat varieties may be a factor implicated in poorer performance in broiler chickens. However, this is in direct contrast to the theory that rapid starch digestion has a negative effect on feed conversion efficiency (Weurding, 2002).

This study found that there was no significant ( $p > 0.05$ ) relationship between soluble NSP and *in vitro* viscosity and indeed positive relationships between *in vitro* viscosity and DMI, LWG, gain:feed and *in vivo* viscosity were observed. However, it must be emphasized that, although the relationships in this study were statistically significant ( $p < 0.05$ ), the correlation coefficients were very poor ( $r = 0.37, 0.34, 0.22$  and  $0.31$  respectively). McCracken et al. (2001) also found poor relationships between feed conversion efficiency and *in vitro* or *in vivo* viscosity (correlation coefficients of  $0.06$  and  $0.32$  respectively). These results add further ambiguity to the relationship between viscosity and bird performance, as it has been reported that an increase in the viscosity of the digesta, brought about by increased soluble NSP, leads to a decrease in liveweight gain and feed conversion efficiency (Bedford et al., 1991; Bedford and Classen, 1992; Dusel et al., 1997). The difference in findings may be attributed to the relatively low *in vivo* viscosity values of the wheat samples used in this study and that of McCracken et al. (2001). However, the low *in vivo* viscosity values are more typical of those from a commercial broiler diet. Although a significant negative relationship between intestinal viscosity and weight gain and feed conversion efficiency was not demonstrated in this study, a negative relationship was found between AME and total and soluble NSP (correlation coefficients of  $-0.43$  and  $-0.30$  respectively). This may add to the findings of several studies that demonstrated that the content of non-starch polysaccharides may be responsible for the low AME of some wheats (Annisson, 1993; Classen et al., 1995; Choct et al., 1999). Choct and Annisson (1992) and Steinfeldt (2001) both reported that the arabinoxylan

content of wheat and wheat-based diets becomes detrimental to chickens when the concentration reaches a certain level. Choct and Annisson (1992) reported highly significant negative correlations between the total pentosan content of the diet and the ileal digestibility coefficients of starch, protein and lipid and Steinfeldt (2001) reported a negative correlation between the dietary arabinoxylan content and the apparent fat digestibility coefficients measured from excreta. In this study, total NSP was significantly ( $p < 0.01$ ) negatively correlated with ileal starch digestibility ( $-0.405$ ), but positively correlated with ileal protein digestibility ( $0.361$ ), DMI ( $0.395$ ) and LWG ( $0.312$ ). Perhaps the level of NSP was not sufficiently high to become detrimental to the performance of the birds, although Choct and Annisson (1992) stated that cereal NSP exhibit anti-nutritive activity at levels as low as  $< 50$  g/kg in broiler diets, which is much lower than those found in this study.

Attempts to establish multiple regression relationships were more successful than single regressions. Correlation coefficient values greater than  $0.8$  were achieved for DMI, LWG, total gain:feed and ileal crude protein digestibility (Table 6). However, the number of parameters and the cost and complexity involved in determining the parameters in the best predictor combinations would be too great to make the process economically worthwhile in a commercial setting. For example, the best correlation coefficient was  $0.863$  for gain:feed, which involved the determination of N, TG, RSD, soluble NSP, protein band 1, NDF and dry matter (as all results reported on a dry matter basis) in duplicate. This equates to an approximate cost of £350 and involves over 15 h of labour.

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## REFERENCES

- Annisson, G. 1990. Complex polysaccharide in poultry diets. Proc. Aust. Poult. Sci. Symp. pp. 17-24.
- Annisson, G. 1993. The role of wheat non-starch polysaccharides in broiler nutrition. Aust. J. Agric. Res. 44:405-422.
- Association of official analytical chemists 1990. Official methods of analysis 15<sup>th</sup> ed., Washington DC, USA: AOAC.
- Austin, S. C., J. Wiseman and A. Chesson. 1999. Influence of non-

- starch polysaccharides structure on the metabolizable energy of UK wheat fed to poultry. *J. Cereal Sci.* 29:77-88.
- 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.
- Bedford, M. R. and H. L. Classen. 1993. An *in vitro* assay for prediction of broiler intestinal viscosity and growth when fed rye-based diets in the presence of exogenous enzymes. *Poult. Sci.* 72:137-143.
- Bedford, M. R. and A. J. Morgan. 1996. The use of enzymes in poultry diets. *World's Poult. Sci. J.* 52:61-68.
- Bedford, M. R., H. L. Classen and G. L. Campbell. 1991. The effect of pelleting, salt and pentosanase on the viscosity of intestinal contents and the performance of broilers fed rye. *Poult. Sci.* 70:1571-1577.
- Carré, B. 2004. Causes for variation in digestibility of starch among feedstuffs. *World Poult. Sci. J.* 60:76-89.
- Carré, B., A. Ida, 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.
- Chesson, A., M. F. Fuller and A. Alldrick. 2002. Wheat and barley in pig and poultry diets: effects of physical processing and enzymes; assessment of nutritive value. Project Report No. 274, HGCA, London.
- Choct, M. and G. Anison. 1992. Anti-nutritive effect of wheat pentosans in broiler chicken: Role of viscosity and gut microflora. *Br. Poult. Sci.* 33:821-834.
- Choct, M., R. J. Hughes, and M. R. Bedford. 1999. Effects 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.
- Classen, H. and T. A. Scott. 1995. Current research on the use of enzymes to improve the nutritional value of wheat and hullless barley for broiler chicken. Proc. 10th Eur. Symp. Poult. Nutr., Antalya, Turkey, pp. 169-175.
- Classen, H., T. A. Scott, G. G. Irish, P. Hucl, M. Swift and M. R. Bedford. 1995. The relationship of chemical and physical measurements to the apparent metabolizable energy (AME) of wheat when fed to broiler chickens with and without an enzyme source. Proc. 10th Eur. Symp. Poult. Nutr., Antalya, Turkey, pp. 169-175.
- Dusel, G., H. Kluge, K. Glaser, O. Simon, G. Hartmann, J. V. Lengerken and H. Jeroch. 1997. An investigation into the variability of extract viscosity of wheat relationship with the content of non-starch polysaccharide fractions and metabolizable energy for broiler chicks. *Arch. Tieremahr.* 50:121-135.
- Englyst, H. N., M. E. Quigley and G. J. Hudson. 1994. Determination of dietary fibre as nonstarch polysaccharides with gas-liquid-chromatographic, high-performance liquid-chromatographic or spectrophotometric measurement of constituent sugars. *Analyst* 119:1497-1509.
- Englyst, H. N., J. Veenstra and G. J. Hudson. 1996. Measurement of rapidly available glucose (RAG) in plant foods: a potential *in vitro* predictor of the glycaemic response. *Br. J. Nutr.* 75:327-337.
- Garnsworthy, P. C., J. Wiseman and K. Fegeros. 2000. Prediction of chemical, nutritive and agronomic characteristics of wheat by near infrared spectroscopy. *J. Agric. Sci. Cambridge.* 135:409-417.
- George, J. 2000. Studies on the relationships between physical and chemical parameters of wheat and their relevance to nutritive value. PhD Thesis, Queen's University, Belfast.
- Hughes, R. J. and M. Choct. 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.
- Hughes, R. J., A. Kocher, L. Acone, P. Langston and J. N. Bird. 1996. Attainable AME and physio-chemical characteristics of xylanase-supplemented wheats. In Proc. Tenth Aust. Poult. Feed Conv., Melbourne, pp. 232-235.
- Leone, J. L. 1973. Collaborative study of the quantitative determination of titanium dioxide in cheese. *J. Assoc. Off. Anal. Chem.* 56:535-537.
- Magee, F. A. 1994. Studies on the nutritive value of wheat-based diets for broilers. MSc Thesis, The Queens's University of Belfast.
- March, B. E. and J. Biely. 1973. Chemical, physical and nutritional characteristics of different samples of wheat. *Can. J. Anim. Sci.* 53:569-577.
- McCleary, B. V., T. S. Gibson and D. C. Mugford. 1997. Measurement of total starch in cereal products by amyloglucosidase- $\alpha$ -amylase method: Collaborative Study. *J. Assoc. Off. Anal. Chem. Int.* 80:571-579.
- McCracken, K. J. and G. Quintin. 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., 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.
- McCracken, K. J., C. M. Preston and C. Butler. 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.
- McNab, J. M. 1991. Factors affecting the nutritive value of wheat for poultry. Project Report No. 43, HGCA, London.
- Miller, H. M., J. M. Wilkinson, K. J. McCracken, A. Knox, J. McNab and C. P. Rose. 2001. Nutritional value to farm livestock of wheat of low specific weight. HGCA Project Report No. 260, HGCA, London.
- Mollah, Y., W. L. Bryden, I. R. Wallis, D. Balnave and E. F. Annison. 1983. Studies on low metabolizable energy wheats for poultry using conventional and rapid assay procedures and the effects of processing. *Br. Poult. Sci.* 24:81-89.
- Ohm, J. B., O. K. Chung and C. W. Deyoe. 1998. Single-kernel characteristics of hard winter wheats in relation to milling and baking quality. *Cereal Chem.* 75:156-161.
- Peddie, J., W. A. Dewar, A. B. Gilbert and D. Waddington. 1982. The use of titanium dioxide for determining apparent digestibility in mature domestic fowls (*Gallus domesticus*). *J. Agric. Sci.* 99:233-236.

- Pirgozliev, V. R., C. L. Birch, C. 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.
- Pirgozliev, V. R., C. P. Rose and R. A. Graybosch. 2002. Energy and amino acid availability to chickens of waxy wheat. *Arch. fur Geflugelkunde* 66:108-113.
- Rafuse, J. L., F. G. Silversides, M. R. Bedford and P. H. Simmins. 2005. Effect of cultivar and enzyme supplementation on nutrient availability and performance of broilers fed Maritime Canadian wheat. *Can. J. Anim. Sci.* 85:493-499.
- Rogel, A. M., E. F. Annison, W. L. Bryden and D. Belnave. 1987. The digestion of wheat starch in broiler chickens. *Aust. J. Agric. Res.* 38:639-649.
- Rooney, L. W. and R. L. Pflugfelder. 1986. Factors affecting starch digestibility with special emphasis on sorghum and corn. *J. Anim. Sci.* 63:1607-1623.
- Rose, S. P., P. S. Kettlewell, M. S. Reynolds and M. R. Watts. 1993. The nutritive value of different wheat varieties for poultry. *Proc. Nutr. Soc.* 52:206A.
- 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.
- Samli, H. E., N. Senkoylu, M. L. Ozduven and A. Agma. 2006. An *in vitro* assessment of nutritional and physical characteristics of wheat varieties obtained from Thrace and Aegean regions for poultry. *Pakistan J. Nutr.* 5:83-85.
- Scott, T. A., F. G. Silversides, H. L. Classen, M. L. Swift and M. R. Bedford. 1998. Effect of cultivar and environment on the feeding value of Western Canadian wheat and barley samples with and without enzyme supplementation. *Can. J. Anim. Sci.* 78:649-656.
- Smits, C. H. M., A. Veldman, M. W. A. Verstegen and A. C. Beynen. 1997. Dietary carboxymethylcellulose with high instead of low viscosity reduces macronutrient digestion in broiler chickens. *J. Nutr.* 127:483-487.
- Steenfeldt, S. 2001. The dietary effect of different wheat cultivars for broiler chickens. *Br. Poult. Sci.* 42:595-609.
- Stoldt, W. 1952. Vorschlarz Zur Vereinheitlichung der Fellbestimmung in Lebensmitteln (Suggestion to standardise the determination of fat in foodstuffs). *Fette Seifn unt Anstrichmittehen*, 54:206-207.
- Van Soest, P. J. 1963. Use of detergents in the analysis of fibrous feeds. 1. Preparation of fibre residues of low nitrogen contents. *J. Assoc. Off. Agric. Chem.* 46:825.
- Waldron, L. A., S. P. Rose and P. S. Kettlewell. 1995. Rate of *in vitro* starch digestion of 2 wheat varieties and its relationship to broiler chicken productive performance. *Br. Poult. Sci.* 36: 875-876.
- Weurding, E. 2002. Kinetics of starch digestion in broilers. PhD Thesis, University of Wageningen.
- Weurding, R. E., A. Veldman, W. A. G. Veen, P. J. Van der Aar and M. W. A. Verstegen. 2001. Starch digestion rate in the small intestine of broiler chickens differs among feedstuffs. *J. Nutr.* 131:2329-2335.
- Wilkinson, J. M., H. M. Miller, K. J. McCracken, A. Knox, J. McNab and S. P. Rose. 2003. Effect of specific weight on the metabolizable energy content of four cultivars of wheat grain in ewes. *Anim. Feed Sci. Technol.* 105:215-224.
- Wiseman, J. and J. Inbarr. 1990. The nutritive value of wheat and its effect on broiler performance. In *Recent Advances in Animal Nutrition* (Ed. W. Haresign and D. J. A Cole). pp. 79-102. Butterworths, London.
- Wiseman, J. and J. McNab. 1995. Nutritive value of wheat varieties fed to non-ruminants. Project Report No. 111, HGCA, London.
- 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., N. T. Nicol and G. Norton. 2000. Relationship between apparent metabolizable (AME) values and *in vivo/in vitro* starch digestibility of wheat for broilers. *World's Poult. Sci. J.* 56:305-318.
- Yun, S. H. and N. K. Matheson. 1990. Estimation of amylase content of starches after precipitation of amylopectin by concanavalin-A. *Starch*, 42:302-305.