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Pre- and post-pellet whole grain inclusions enhance feed conversion efficiency, energy utilisation and gut integrity in broiler chickens offered wheat-based diets

Ha H. Truong[a,b], Amy F. Moss[a], Sonia Yun Liu[a], Peter H. Selle[a,*]

[a] Poultry Research Foundation within The University of Sydney, NSW, Australia
[b] Poultry CRC, University of New England, Armidale, NSW, Australia

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ABSTRACT

In order to investigate whole grain feeding strategies seven dietary treatments were offered to 8 replicates (6 birds per cage) of male Ross 308 chicks from 7 to 28 days post-hatch. A steam-pelleted, wheat-based diet in which the wheat had been ground through a 3.2 mm hammer-mill screen served as the control. Whole wheat was added at 4.5, 9.0 and 18.0% of the diet in substitution for ground wheat and whole wheat was incorporated into the ration either pre- or post-pelleting. For post-pelleting additions, whole wheat and pelleted concentrate were blended. The effects of dietary treatments on relative gizzard and pancreas weights, gizzard contents and their pH and the incidence of dilated proventriculi were assessed. Treatment effects on growth performance and nutrient utilisation (AME as MJ/kg and MJ/day, ME:GE ratios, N retention and AMEn) were determined. Effects of treatments on starch and protein (N) digestibility coefficients and disappearance rates in the distal ileum were investigated on the basis of inherent AIA dietary concentrations and starch concentrations in the distal ileum were considered. Feed and water intakes and dry matter of excreta over the total excreta collection period were determined. Post-pellet inclusions of whole wheat had greater impacts on bird performance than whole wheat additions prior to pelleting. Relative to the ground grain control diet, post-pellet whole wheat inclusions increased relative gizzard weights, reduced gizzard digesta pH, reduced the incidence of dilated proventriculi, improved feed conversion ratios, ostensibly increased starch digestibility coefficients and disappearance rates in the distal ileum and reduced residual starch concentrations in the distal ileum. Additionally, post-pellet whole wheat inclusions unequivocally enhanced all nutrient utilisation parameters. Collectively, post-pellet whole wheat inclusion increased relative gizzard weights by 26.1% (18.35 versus 14.55 g/kg; $P < 0.001$), reduced the incidence of dilated proventriculi from 8.4 to 0.7% ($P < 0.02$), improved FCR by 4.25% (1.442 versus 1.506; $P < 0.003$), increased AME by 0.81 MJ (12.88 versus 12.07 MJ/kg; $P < 0.005$)) and enhanced ME:GE ratios by 6.14% (0.743 versus 0.700; $P < 0.005$). The 18.0% pre-pellet inclusion of whole grain increased relative gizzard weights by 13.0% (16.44 versus 14.55 g/kg; $P < 0.005$), improved FCR by 5.51% (1.423 versus 1.506; $P < 0.001$) and enhanced AME by 0.59 MJ (12.66 versus 12.07 MJ/kg; $P < 0.005$).

Abbreviations: AIA, acid insoluble ash; AME, apparent metabolisable energy; FCR, feed conversion ratio; GE, gross energy; ME, metabolisable energy; N, nitrogen; NIR, near infrared spectroscopy; NSP, non-starch polysaccharide.

* Corresponding author.
E-mail address: peter.selle@sydney.edu.au (P.H. Selle).

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This study confirms the advantages of whole grain feeding in the context of broiler chicken performance which appeared to be driven by greater extents of starch digestion allied to heavier relative gizzard weights.

1. Introduction

The strategy of whole grain feeding has met with increasing acceptance in chicken-meat production in countries where wheat is the dominant feed grain including parts of Europe, Canada and Australasia. In both Australia and New Zealand chicken-meat production is extensively integrated; however, in Australia whole wheat is routinely added 'post-pelleting' and the ration is a blend of whole wheat and a pelleted balancing concentrate. In contrast, for reasons of compliance, in New Zealand whole wheat is usually incorporated into the diet prior to steam-pelleting and with these 'pre-pelleting' additions the ration takes the form of intact pellets in which whole wheat is embedded.

The strategy of whole grain feeding has been recently reviewed by Singh et al. (2014) and Liu et al. (2015). The impression emerges from both papers that the level of acceptance of whole grain feeding in practice exceeds the extent of research completed to under-pin the strategy. The factors driving the acceptance of whole grain feeding by integrated operations appear to range from reduced feed-milling costs and increased feed-milling capacity to enhanced 'gut integrity' and a reduced likelihood of production and welfare issues associated with wet litter (Dunlop et al., 2016). Within this range is the probability that whole grain feeding enhances feed conversion efficiency and energy utilisation which is usually attributed to heavier relative gizzard weights and, presumably, improved gizzard and gut function.

Wu et al. (2004) reported improvements in energy utilisation (AME) from pre-pellet 20% whole grain addition that could not be attributed to heavier relative gizzard weights. Thus alternative or additional mechanisms whereby whole grain feeding enhances broiler performance are of interest. For example, Hetland et al. (2002) found whole grain feeding reduced duodenal particle size and, presumably as a consequence, improved starch digestibility. The core objective of this study was to determine the impact of graded (4.5, 9.0 and 18.0%) pre-pellet and post-pellet whole grain additions on growth performance and nutrient utilisation of broiler chickens offered wheat-based diets.

2. Materials and methods

A wheat-based diet (600 g/kg) was formulated to meet the recommended requirements for male Ross 308 chicks from 7 to 28 days post-hatch (Table 1). The wheat had been characterised by near-infrared spectroscopy (NIR) and the AusScan program (Pork CRC Ltd. Willaston, South Australia), which also appears in Table 1. The seven dietary treatments consisted of a control diet in which the entire grain component was ground through a 3.2 mm hammer-mill screen prior to steam-pelleting through a 4.00 mm die at a temperature of 80 °C and a 14 s residence time in the conditioner. In the balance of the six dietary treatments 45, 90 and 180 g/kg whole wheat inclusions were incorporated into the diets at the expense of ground wheat either pre- or post-pelleting. In the case of post-pellet additions the ration was prepared by mixing the whole grain and the pelleted concentrate.

Each of the seven dietary treatments was offered to 8 replicate cages (6 birds per cage) or a total of 336 male (feather-sexed) Ross 308 chicks from 7 to 28 days post-hatch in an environmentally controlled facility under a '16-h-on' lighting regime. Initially the birds were offered a proprietary starter ration under a '23-h-on' lighting regime and at 7 days post-hatch they were weighed and allocated into 56 cages so that body-weights and their standard deviations were nearly identical.

Total excreta from each cage were collected and weighed and feed intake specifically monitored from 26 to 28 days post-hatch to determine apparent metabolisable energy (AME as MJ/kg and MJ/day), metabolisable to gross energy (ME:GE) ratios, nitrogen (N) retention and N-corrected AME (AMEn) on a dry matter basis. Feed and water intakes were recorded over this 48 h period and excreta dry matter determined after excreta were air-forced oven dried for 24 h at 80 °C. Gross energy (GE) of diets and excreta were determined using a Parr 1281 adiabatic bomb calorimeter (Parr Instrument Co., Moline, IL. USA). AME values (MJ/kg) of the diet were calculated using the following formula:

$$AME_{diet} = \frac{(\text{Feed intake} \times GE_{diet}) - (\text{Excreta output} \times GE_{excreta})}{(\text{Feed intake})}$$

Energy intakes (AME; MJ/day) were determined by dividing AME (MJ/kg) by daily feed intakes over the total excreta collection period. ME:GE ratios were calculated by dividing AME values recorded for each cage by GE of the relevant diets. N content of the diets and excreta were obtained using an FP-428 determinator (Leco Corporation, St Joseph, MI. USA). N retention was calculated using the following formula:

$$\text{N retention}\,(\%) = \frac{(\text{Feed intake} \times N_{diet}) - (\text{Excreta output} \times N_{excreta})}{(\text{Feed intake} \times N_{diet})} \times 100$$

N-corrected AME (AMEn MJ/kg) values were calculated by correcting to zero N retention by applying the factor of 36.54 kJ/g N retained in the body (Hill and Anderson, 1958).

Table 1
Composition and nutrient specifications of wheat-based diet and NIR AusScan characteristics of wheat.

Item (g/kg, as-is)	Diet	Wheat	AusScan (g/kg, as-is)
Composition	600.0	AME broilers (MJ/kg as-fed)	12.4
Wheat[a]	239.2	NIR Protein	132
Soybean meal	72.8	Total starch	719
Canola meal	49.0	Crude fibre	31
Canola oil	17.6	Acid detergent fibre	36
Dicalcium phosphate	8.0	Neutral detergent fibre	4
Limestone	2.7	Total soluble NSP	83
Lysine HCl	2.3	Total insoluble NSP	69
Methionine	0.9	Insoluble arabinoxylans	69
Threonine	1.6	Hydration capacity (%)	27.5
Sodium chloride	3.9		
Sodium bicarbonate	2.0		
Vitamin-mineral premix[b]	12.55		
Nutrient specifications	215.3		
ME (MJ/kg)	366.7		
Protein	68.5		
Starch	8.0		
Fat	6.8		
Calcium	4.0		
Total phosphorus	12.7		
Available phosphorus	5.6		
Lysine	8.8		
Methionine	8.5		
Threonine	2.8		
Isoleucine	3.8		
Tryptophan	9.7		
Cystine	13.2		
Valine	5.3		
Arginine	15.1		
Histidine	9.7		
Leucine	1.8		
Phenylalanine	7.8		
Sodium	2.1		
Potassium			
Chloride			

[a] Ground wheat; in the pre- and post-pellet whole grain diets, 45 g, 90 g and 180 g of whole wheat replaced ground wheat in the 4.5%, 9% and 18% whole grain dietary treatments, respectively.
[b] The vitamin-mineral premix supplied per tonne of feed: [MIU] retinol 12, cholecalciferol 5, [g] tocopherol 50, menadione 3, thiamine 3, riboflavin 9, pyridoxine 5, cobalamin 0.025, niacin 50, pantothenate 18, folate 2, biotin 0.2, copper 20, iron 40, manganese 110, cobalt 0.25, iodine 1, molybdenum 2, zinc 90, selenium 0.3.

On day 28, birds were weighed and euthanised (intravenous injection of sodium pentobarbitone) and feed intakes recorded. Feed conversion ratios (FCR) were calculated from weight gains and feed intakes where the body weights of any dead or culled birds were used to adjust feed intakes. Weights of full end emptied gizzards and pancreases were determined and expressed on a relative basis to total body weight. The pH of gizzard contents *in situ* was determined. During this procedure an unusually high incidence of grossly dilated proventriculi was noticed and therefore recorded. Digesta from the distal half of the ileum was collected in its entirety. The digesta samples were freeze-dried and inherent dietary acid insoluble ash (AIA) concentrations were determined by the method of Siriwan et al. (1993). N concentrations were determined as outlined above and starch concentrations in diets and digesta were determined by a procedure based on dimethyl sulfoxide, α-amylase and amyloglucosidase, as described by Mahasukhonthachat et al. (2010). On the basis of inherent dietary AIA concentrations, apparent digestibility coefficients for crude protein (N) and starch in the distal ileum were calculated from the following equation:

$$\text{Apparent digestibility coefficient} = \frac{\left(\%\,\text{nutrient}/\%\text{AIA}\right)_{\text{diet}} - \left(\%\,\text{nutrient}/\%\text{AIA}\right)_{\text{digesta}}}{\left(\%\,\text{nutrient}/\%\text{AIA}\right)_{\text{diet}}}$$

Apparent disappearance rates of N and starch at the distal ileaum were calculated from their analysed dietary concentrations, feed intakes over the final 48 h of the feeding study expressed on a daily basis, and apparent digestibility coefficients from the following equation:

Apparent disappearance rate (g/bird/day) = nutrient dietary concentration (g/kg)
*daily feed intake (g/bird)*nutrient digestibility coefficient.

Experimental data were analysed using the IBM® SPSS® Statistics 20 program (IBM Corporation. Somers, NY USA). Statistical procedures included univariate analyses of variance using the general linear models procedure, linear regressions and

Table 2
The effects of dietary treatments on relative gizzard and pancreas weights, pH of gizzard digesta, relative gizzard contents and incidence of dilated proventriculi.

Treatment	Relative gizzard weight (g/kg)	Relative pancreas weight (g/kg)	Gizzard digesta pH	Relative gizzard contents (g/kg)	Dilated proventriculi (%)
Control	14.55a	2.22ab	3.46c	2.4a	8.35b
Pre-pellet 4.5%	15.22ab	2.41bc	3.41bc	4.8b	2.09a
whole 9.0%	15.36ab	2.17a	3.52c	4.7b	0.00a
grain 18.0%	16.44bc	2.38bc	3.37bc	6.5b	2.09a
Post-pellet 4.5%	16.89c	2.40bc	3.13ab	9.1c	0.00a
whole 9.0%	18.14d	2.51c	3.13ab	9.6c	2.09a
grain 18.0%	20.01e	2.33abc	3.07a	10.1c	0.00a
SEM	0.3813	0.0698	0.1031	0.7243	1.8140
Significance (P=)	<0.001	0.022	0.010	<0.001	0.026
LSD (P < 0.05)	1.084	0.198	0.293	2.058	5.155

abcde: Means within columns not sharing a common suffix are significantly different at the 5% level of probability.

Table 3
The effects of dietary treatments on growth performance from 7 to 28 days post-hatch.

Treatment	Weight gain (g/bird)	Feed intake (g/bird)	FCR (g/g)	Mortality rate (%)
Control	1638b	2466c	1.506a	2.08
Pre-pellet 4.5%	1667b	2410bc	1.446b	4.17
whole 9.0%	1672b	2421bc	1.449b	0.00
grain 18.0%	1657b	2358ab	1.423b	0.00
Post-pellet 4.5%	1669b	2391abc	1.433b	0.00
whole 9.0%	1645b	2366ab	1.439b	0.00
grain 18.0%	1587a	2305a	1.453b	0.00
SEM	17.907	31.573	0.0158	1.2975
Significance (P=)	0.022	0.025	0.028	0.168
LSD (P < 0.05)	50.9	89.7	0.0449	–

abc: Means within columns not sharing a common suffix are significantly different at the 5% level of probability.

Pearson correlations. A probability level of less than 5% was considered to be statistically significant. The feeding study was conducted so as to comply with specific guidelines approved by the Animal Ethics Committee of The University of Sydney.

3. Results

The effects of dietary treatments on relative gizzard and pancreas weights, pH of gizzard digesta, relative gizzard contents and incidence of dilated proventriculi are shown in Table 2. There was a significant treatment effect (P < 0.001) on relative gizzard weights where the highest pre-pellet whole grain addition of 18% significantly increased relative gizzard weights by 13.0% (16.44 versus 14.55 g/kg) but the lower pre-pellet whole grain additions did not generate significant increases. In contrast, graded post-pellet whole grain additions significantly increased relative gizzard weights by 16.1, 24.7 and 37.5% at 4.5, 9.0 and 18.0%, respectively. There was a significant treatment effect (P < 0.025) on relative pancreas weights but the pattern of results lacked consistency. There was a significant treatment effect (P < 0.01) on gizzard digesta pH where post-pellet whole grain additions reduced pH from 3.46 to values ranging from 3.13 to 3.07. There was a significant treatment effect (P < 0.001) on relative gizzard contents where pre-pellet whole grain addition increased contents by a factor of 2.21 from 2.4 g/kg to an average of 5.3 g/kg and post-pellet whole grain addition increased contents by a four-fold factor to an average of 9.6 g/kg. There was a significant treatment effect (P < 0.03) on the incidence of dilated proventriculi. The incidence of dilated proventriculi was 8.35% in the ground grain control group but the overall average incidence in all the whole grain treatments was 1.05%.

The effects of dietary treatments on growth performance from 7 to 28 days post-hatch are shown in Table 3. The overall low mortality/cull rate of 0.89% was not influenced by treatment (P > 0.15). There was a significant treatment effect (P < 0.025) on weight gain where 18.0% post-pellet whole grain generated a weight gain of 1587 g/bird which was significantly less than the other six treatments which averaged 1658 g/bird by 4.28%. There was a significant treatment effect (P < 0.025) on feed intake; the ground grain control group had a feed intake of 2466 g/bird which was significantly reduced by 18% pre-pellet whole grain by 4.38% to 2358 g/bird, 9% post-pellet whole grain by 4.06% to 2366 g/bird and by 18% post-pellet whole grain by 6.53% to 2305 g/bird. The remaining whole grain additions did not statistically influence feed intake. There was a significant treatment effect (P < 0.03) on feed conversion ratios; the ground grain control treatment generated a FCR of 1.506 which was significantly improved by all pre- and post-pellet whole grain additions. On average, whole grain inclusions improved FCR by 4.32% (1.441 versus 1.506) with a peak improvement of 5.51% (1.423 versus 1.506) in response to 18% pre-pellet whole grain addition.

The highly significant (P = 0.006 –<0.001) dietary treatments effects on AME (MJ/kg and MJ/day), ME:GE ratios, N retention and AMEn are shown in Table 4. Pre-pellet whole grain addition at 18% significantly improved AME by 0.59 MJ (12.66 versus

Table 4
The effects of dietary treatments on apparent metabolisable energy (AME MJ/kg, MJ/day), metabolisable energy to gross energy ratios (ME:GE), nitrogen (N) retention and N-corrected AME (AMEn) from 26 to 28 days post-hatch.

Treatment	AME (MJ/kg DM)	ME:GE ratio	AME (MJ/day)	N retention (%)	AMEn (MJ/kg DM)
Control	12.07a	0.700a	1.92a	58.79ab	11.02a
Pre-pellet 4.5%	12.09a	0.700a	1.91a	60.27abc	11.07a
whole 9.0%	12.07a	0.703a	2.01ab	57.29a	11.05a
grain 18.0%	12.66b	0.727b	2.02ab	61.57bc	11.58bc
Post-pellet 4.5%	12.67b	0.731b	2.07b	63.59cd	11.55b
whole 9.0%	12.86bc	0.744bc	2.11b	66.31de	11.65bc
grain 18.0%	13.13c	0.753c	2.08b	68.55e	11.91c
SEM	0.1245	0.0072	0.0418	1.4725	0.1173
Significance (P =)	<0.001	<0.001	0.006	<0.001	<0.001
LSD (P < 0.05)	0.354	0.0204	0.119	4.059	0.333

abcde: Means within columns not sharing a common suffix are significantly different at the 5% level of probability.

Table 5
The effects of dietary treatments on water intake, feed intake, water to feed intake ratios and excreta dry matter during the total excreta collection period.

Treatment	Water intake (g/bird/day)	Feed intake (g/bird/day)	Water to feed intake ratio	Excreta dry matter (%)[a]
Control	340	163	2.09	31.83b
Pre-pellet 4.5%	347	162	2.15	29.00ab
whole 9.0%	359	167	2.16	28.79ab
grain 18.0%	358	159	2.25	28.01a
Post-pellet 4.5%	356	164	2.18	27.45a
whole 9.0%	355	164	2.17	28.27a
grain 18.0%	364	159	2.29	26.34a
SEM	8.508	3.003	0.0559	1.0893
Significance (P =)	0.461	0.568	0.212	0.037
LSD (P < 0.05)	–	–	–	3.096

ab: Means within columns not sharing a common suffix are significantly different at the 5% level of probability.
[a] Excreta dry matter is correlated with water intake (r = –0.435; < 0.001), feed intake (r = 0.414; P = 0.002) and water:feed ratios (r = –0.379; P = 0.004).

12.07 MJ/kg) and 18% post-pellet whole grain generated an improvement of 1.06 MJ (13.13 versus 12.07 MJ/kg). Post-pellet whole grain inclusions of 4.5 and 9% significantly improved AME by 0.60 and 0.79 MJ, respectively. Post-pellet whole grain inclusions significantly increased energy intakes (AME; MJ/day) by an average of 8.85% (1.92 versus 2.09 MJ/day). The pre-pellet whole grain inclusion of 18% significantly enhanced ME:GE ratios by 3.86% (0.727 versus 0.700); whereas, increasing post-pellet whole grain enhanced ME:GE ratios by 4.43, 6.29 and 7.57%, respectively. Post-pellet whole grain inclusion enhanced N retention by 4.80 percentage units (63.59 versus 58.79%) at 4.5%, 7.52 percentage units (66.31 versus 58.79%) at 9% and by 9.76 percentage units (68.55 versus 58.79%) at 18% whole grain. Pre-pellet whole grain addition at 18% significantly improved AMEn by 0.56 MJ (11.58 versus 11.02 MJ/kg) and 18% post-pellet whole grain generated an improvement of 0.89 MJ (11.91 versus 11.02 MJ/kg). Post-pellet whole grain inclusions of 4.5 and 9% significantly improved AMEn by 0.53 and 0.63 MJ, respectively.

The effects of dietary treatments on water intake, feed intake, water to feed intake ratios and excreta dry matter during the total excreta collection period are shown in Table 5. Significant treatment effects (P < 0.04) were confined to excreta dry matter. The three post-pellet whole grain and 18% pre-pellet whole grain inclusions collectively reduced excreta dry matter from 31.83% by 4.30 percentage units to an average of 27.52%.

The effects of dietary treatments on starch and protein (N) digestibility coefficients and disappearance rates (g/bird/day) in the distal ileum, distal ileal starch:protein disappearance rate ratios and distal ileal starch concentrations are shown in Table 6. This data should be treated with caution as it is based solely on the inherent dietary AIA concentrations which averaged 0.187% with a range 0.104–0.224%. However, the starch outcomes, if not protein (N) results, appear quite reasonable; nevertheless, the protein (N) results are tabulated for the sake of completeness. On this basis, there was a significant treatment effect on distal ileal starch digestibility coefficients. Collectively, post-pellet whole grain inclusions increased starch digestibility by 24.3% from 0.746 in the control ground grain treatments to an average of 0.927. Similarly, post-pellet whole grain inclusions increased starch disappearance rates by 19.4% from 25.3 g/bird/day in the control to an average of 30.2 g/bird/day in post-pellet whole grain treatments. Absolute starch concentrations in the distal ileum are instructive where a significant treatment effect (P < 0.001) was observed but pre-pellet whole grain inclusions did not change this parameter statistically. In contrast, post-pellet whole grain inclusions collectively reduced distal ileal starch concentrations by 50.4% from 14.53 to an average of 7.21 g/100 g.

Therefore, Pearson correlations between both distal ileal starch concentrations and relative gizzard weights with parameters of nutrient utilisation are shown in Table 7. There is a negative correlation (r = –0.538; P < 0.001) between relative gizzard weights and distal ileal starch concentrations. Moreover, both relative gizzard weights and distal ileal starch con-

Table 6
The effects of dietary treatments starch and protein (N) digestibility coefficients and disappearance rates (g/bird/day) in the distal ileum, distal ileal starch:protein disappearance rate ratios and distal ileal starch concentrations.

Treatment	Starch		Protein (N)		Starch:protein disappearance rate ratio	Distal ileal starch concentration (g/100 g)
	Digestibility coefficient	Disappearance rate	Digestibility coefficient	Disappearance rate		
Control	0.746ab	25.3b	0.708ab	17.0ab	1.45a	14.53b
Pre-pellet 4.5%	0.674a	21.5a	0.664a	15.7a	1.37a	16.39b
whole 9.0%	0.826bc	30.8d	0.770b	18.1b	1.71c	15.78b
grain 18.0%	0.809b	26.9bc	0.717ab	17.9b	1.53ab	16.16b
Post-pellet 4.5%	0.939d	30.8d	0.869c	20.4c	1.51ab	8.90a
whole 9.0%	0.931d	30.3d	0.771b	18.4b	1.65bc	5.74a
grain 18.0%	0.911cd	29.4cd	0.750b	17.7b	1.68bc	6.98a
SEM	0.0354	1.1702	0.0252	0.6542	0.1904	1.6500
Significance ($P=$)	<0.001	<0.001	<0.001	<0.001	0.001	<0.001
LSD ($P<0.05$)	0.1005	3.33	0.0717	1.859	0.1711	4.689

abcd: Means within columns not sharing a common suffix are significantly different at the 5% level of probability.

Table 7
Pearson correlations between relative gizzard weights, distal ileal starch concentrations and parameters of nutrient utilisation.

Items	Relative gizzard weight	Distal ileal starch	AME (MJ/kg)	AME (MJ/day)	ME:GE ratio	N retention (%)	AMEn (MJ/kg)
Relative gizzard weight	1.000						
Distal ileal starch	−0.538 $P<0.001$	1.000					
AME (MJ/kg)	0.650 $P<0.001$	−0.488 $P<0.001$	1.000				
AME (MJ/day)	0.361 $P=0.006$	−0.326 $P=0.014$	0.646 $P<0.001$	1.000			
ME:GE ratio	0.622 $P<0.001$	−0.492 $P<0.001$	0.995 $P<0.001$	0.667 $P<0.001$	1.000		
N retention (%)	0.630 $P<0.001$	−0.417 $P=0.001$	0.677 $P<0.001$	0.468 $P<0.001$	0.660 $P<0.001$	1.000	
AMEn (MJ/kg)	0.592 $P<0.001$	−0.452 $P<0.001$	0.978 $P<0.001$	0.563 $P<0.001$	0.973 $P<0.001$	0.545 $P<0.001$	1.000

centrations are, respectively, positively and negatively correlated with AME (MJ/kg), ME:GE ratios, N retention and AMEn to highly significant ($P<0.001$) extents.

4. Discussion

In the present study, the post-pelleting addition of 18% whole wheat significantly depressed feed intake and weight gain by 3.11% and 6.53%, respectively, but enhanced FCR by 3.52% (1.453 versus 1.506). Similar improvements in FCR frpm whole grain feeding have been reported by Plavnik et al. (2002) and Gabriel et al. (2008). The same dietary treatment significantly increased AME by 1.06 MJ, AMEn by 0.89 MJ and improved ME:GE ratios by 7.6% (0.753 versus 0.700). Preston et al. (2000) and Biggs and Parsons (2009) have reported similar improvements in energy utilisation from whole grain feeding.

Additional reasons for the adoption of whole grain feeding regimes include the rationale that whole grain feeding enhances ‘gut integrity’ in broiler chickens. Arguably, relative gizzard weights are an indication of gut integrity; however, it is noteworthy that whole grain treatments collectively reduced the incidence of grossly dilated proventriculi from 8.4% to 1.1%. This outcome is supported by Taylor and Jones (2004b) who reported a reduced incidence of proventricular dilatation following the dietary addition of 20% whole wheat prior to pelleting., This reduction in the incidence of dilated proventriculi generated by whole grain feeding may be a reflection of enhanced gut integrity and may have amplified the responses generated by whole grain feeding.

In the present study 18% whole grain increased relative gizzard weights by 13.0% following pre-pellet addition and by 37.5% from post-pellet addition. It may be deduced from the Liu et al. (2015) review that in 10 sets of observations 18.6% post-pellet whole grain addition increased relative gizzard weights by an average of 39.5%. Similarly, in an overview, Svihus (2011) found that an average of 26.4% (range: 10–50%) whole wheat addition increased relative gizzard weights by 38.7%; however, responses ranged from 7 to 101%. While the mean outcomes are in agreement it should be stressed that gizzard mass responses to whole grain inclusions are extremely inconsistent. It was anticipated from earlier studies (Jones and Taylor, 2001; Taylor and Jones 2004a; Wu et al., 2004) that pre-pellet whole grain addition would not generate comparable

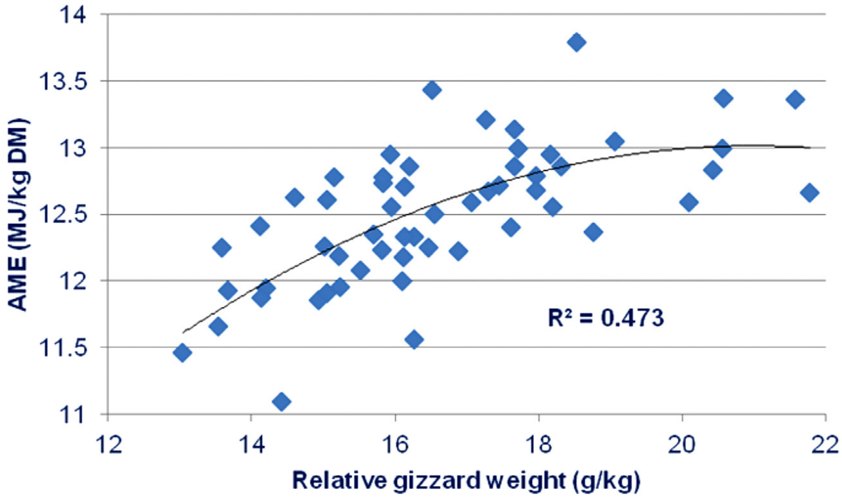

Fig. 1. Quadratic relationship ($r = 0.687$; $P < 0.001$) between relative gizzard weights and AME (cage means) where. $y_{(AME)} = 3.192 + 0.936{*}gizzard_{(g/kg)} - 0.022{*}gizzard_{(g/kg)}^2$

increases in gizzard mass probably because steam-pelleting 'crushes' whole wheat as it is propelled through the die of the pellet press.

The landmark response to whole grain feeding is increased relative gizzard weights. For example, Singh et al. (2014) reviewed ten studies involving 18 paired sets of observations in which relative gizzard weight was increased by an average of 44.0% with a broad range from 18.2 to 100.0%. The consequences of heavier relative gizzard weights lack precise definitions despite the magnitude of the increases in gizzard mass and, presumably, function. Increased retention times of digesta in the gizzard and retarded gut passage rates would appear to be logical corollaries but they have not been unequivocally confirmed (Liu et al., 2015). The phenomenon of reverse peristalsis in poultry is established (Sacranie et al., 2007); however, Ferket (2000) described the gizzard as the 'pace-maker' of gut motility and reverse peristalsis in broiler chickens. Two episodes of reverse peristalsis described by Ferket (2000) are of relevance. The gastric reflux recycles digesta from the gizzard back into the proventriculus via gastro-duodenal contractions. The small intestinal reflux recycles digesta from the duodenum and jejunum back into the gastric area. The likelihood is that the small intestinal or the gastro-duodenal reflux under whole grain feeding regimes will increase the exposure of digesta in the gizzard to the array of pancreatic digestive enzymes including α-amylase in addition to pepsin secreted in the proventriculus.

In the present study, pre-pellet whole grain addition collectively improved FCR by 4.45% (1.439 versus 1.506) as opposed to an improvement of 4.05% (1.442 versus 1.506) following post-pellet whole wheat addition. Clearly these feed efficiency responses are not aligned with the corresponding increases in relative gizzard weights of 7.70 and 26.1%, respectively. This draws attention to the issue, initially raised by Wu et al. (2004) and subsequently considered by Liu et al. (2015) and Truong et al. (2015), that it is not appropriate to attribute whole grain feeding responses entirely to heavier gizzard weights. Truong et al. (2015) contended that whole grain feeding may generate more slowly digestible starch simply because hammer-milling and steam-pelleting grain will accelerate starch digestion rates. Under *in vitro* conditions, Giuberti et al. (2012) reported that steam-flaking increased rapidly digestible starch in maize, wheat and barley. Selle et al. (2013) offered broiler chickens sorghum-based diets as either unprocessed mash or as reground mash following steam-pelleting at 90 °C. Processing the diet increased the proximal jejunal starch digestibility coefficients by 48% from 0.395 to 0.586 which indicates that the digestion rate of unprocessed (whole) grain is inherently slower than processed grain. However, it appears that the fact that pre-pellet and post-pellet whole grain generated very similar FCR responses perhaps should be attributed to the reduced incidence of dilated proventriculi rather than changes in starch digestive dynamics.

Rogel et al. (1987) demonstrated that heavier gizzards generated by fibrous feedstuffs have the potential to increase the extent of starch digestion. Oat hulls increased gizzard weights by 49% (22.15 versus 14.88 g/kg) and raw potato starch digestibility coefficients by 69% (0.926 versus 0.547) in broiler chickens. Moreover, gizzard weights were significantly correlated with starch digestibility coefficients across treatments. In the present study, post-pellet whole wheat additions increased ileal starch digestibilities and ileal starch disappearance coupled with decreased starch concentrations in the distal ileum. Thus, whole grain feeding appeared to increase the extent of starch digestion under the caveat that inherent AIA concentrations in the diets were used as the inert marker. It follows that the greater physical disruption of starch granules and endosperm protein matrices by the grinding action of heavier, more muscular gizzards facilitates substrate access for amylase in the small intestine. Moreover, there is the likelihood that increased episodes of reverse gastro-duodenal peristalsis and the reflux of pancreatic amylase into the gizzard amplifies the extent of starch digestion. Support for this is provided by Hetland et al. (2003) who found adding wood shavings to wheat-based diets increased total amounts of bile acids in the gizzards of layers, which was attributed to increased gastro-duodenal reflux.

Truong et al. (2015) found a mean ileal starch digestibility coefficient of 0.916 (range 0.796–0.990) from nine broiler feeding studies involving 18 paired observations. Thus the increase in digestibility coefficients from 0.746 in ground wheat control diets to an average of 0.927 in the three post-pellet wheat treatments calculated on the basis of inherent dietary AIA appear plausible as the experimental diets did not contain a NSP-degrading feed enzyme. Also relative gizzard weights and distal ileal starch concentrations were negatively correlated to significant extents. In turn, both factors were significantly correlated to the assessed nutrient utilisation parameters (Table 7).

In the Liu et al. (2015) review whole grain feeding increased energy utilisation by an average of 0.83 MJ from 13.37 to 14.20 MJ/kg, this outcome was based on seven reports involving 23 paired observations. In the present study, 18% pre-pellet whole grain increased AME by 0.59 MJ and 4.5, 9 and 18% post-pellet whole grain additions increased AME by 0.60, 0.79 and 1.06 MJ, respectively. Thus these outcomes are in agreement with energy utilisation responses reported in the literature. The significant quadratic relationship between relative gizzard weights and AME is shown in Fig. 1. The relevant regression equation indicates that the maximal AME of 12.15 MJ/kg would be generated by a relative gizzard weight of 21.27 g/kg. It is reasonable to attribute the improvements in nutrient utilisation observed in the present study to the more extensive digestion of starch generated by whole grain feeding, especially following post-pelleting whole wheat additions.

That all post-pellet and 18% pre-pellet whole wheat inclusions reduced excreta dry matter was not expected. However, whole grain feeding did not influence feed and water intakes or their relativity over the total excreta collection period; thus, this finding may be spurious.

5. Conclusion

The post-pellet inclusions of whole wheat at 4.5, 9.0 and 18.0% into broiler rations had substantially greater impacts on bird performance than the corresponding inclusions prior to steam-pelleting diets. Relative to the ground grain control diet, post-pellet whole wheat inclusions increased relative gizzard weights, reduced gizzard digesta pH, reduced the incidence of dilated proventriculi, improved feed conversion ratios, appeared to increase starch digestibility coefficients and disappearance rates in the distal ileum and reduced concentrations of starch remaining in the distal ileum. Additionally, post-pellet whole wheat inclusions unequivocally enhanced AME (MJ/kg, MJ/day), ME:GE ratios, N retention and AMEn.

Conflict of interest

The authors declare that there are not any conflicts of interest.

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