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Efficiency of Utilization of Metabolizable Energy for Carcass Energy Retention in Broiler Chickens Fed Maize, Wheat or a Mixture

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Abstract: The study aimed to quantify carcass fat and protein retention, and the efficiency of carcass energy utilization (Kre) resulting from feeding broiler chickens diets containing wheat, maize or mixtures of both as the major cereal ingredient. The apparent metabolizable energy (AME) of the four cereal samples was determined in adult cockerels. There was a linear ($p < 0.001$) increase in AME with increasing amounts of maize within the four cereal mixtures, with analyses indicating that the AME of maize was 1.4 MJ/kg greater than that of wheat. A second bioassay with growing chickens was used to determine Kre in each cereal, measured as carcass fat and protein from 7 to 21d age. Increasing proportions of maize resulted in linear increases in carcass fat and energy retained from fat ($p < 0.001$). However, the carcass protein and energy retained from protein did not follow the same pattern as fat ($p = 0.121$), but rather decreased numerically (L = 0.032). The Kre tended ($p = 0.060$) to increase with greater proportion of maize in a linear fashion (L = 0.009). Although AME values of cereals were confirmed to be additive, this could not be confirmed for Kre. This data can be used for optimizing energy utilization models for growing broilers.

Keywords: maize; wheat; broilers; metabolizable energy; efficiency of energy utilization

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1. Introduction

Feed materials, such as wheat and maize, are known to be major variables when formulating poultry diets, as their nutrient profile and quality are often inconsistent and deviate from default values used by feed formulation software [1]. Additionally, the feed industry has access to a wide range of feedstuffs and the use of a particular ingredient will often depend on its cost, since least cost formulation algorithms are the industry standard [2]. Whilst commodity ingredient prices fluctuate with market forces, the nutrient composition and available energy content are still the main considerations for nutritionists [3]. Therefore, it is important that accurate predictions of bioavailable energy and nutrient content are available.

When formulating diets for poultry and pigs, it is accepted that the energy and nutrients in dietary ingredients can be added together to supply the required nutrient brought by the diet [4]. The concept of nutrient additivity in diets was studied in swine [5,6], broilers [7–9] and ducks [10]. However, these authors pointed out that the metabolizable energy and amino acid values may not always be additive due to some associative effects. Apparent metabolizable energy (AME) is the most used system to describe the available energy concentration in poultry feeds [11–14]. However, even if diets are formulated to contain the same AME, the efficiency of AME utilization when fed to poultry may differ [15,16]. Different metabolizable nutrients (protein, fat and carbohydrate) are utilized with different relative efficiencies for energy deposition [17–20] and some apparently available nutrients may be fermented in the lower digestive tract. For example, values obtained by AME system usually underestimate the efficiency of utilization of fats and fat-rich ingredients but overestimates protein-rich feedstuffs when compared to carbohydrates [18]. In addition, research in feeding wheat to broilers [21] found no differences in determined AME concentrations of the experimental samples, although there was a difference in efficiency of energy retention that was partially explained by the wheat viscosity. However, even small differences in the efficiency of dietary energy and nutrient utilization may be economically important in the commercial poultry meat industry. Understanding energy and nutrient retention is therefore required in the era of precision feeding.

Cereals or other high starch feedstuffs are the main component in many practical poultry diets and are used mainly to satisfy the energy requirement of the animals [2,22]. Dietary available energy accounts for approximately half the economic cost of broiler chicken feed. Although a wide variety of grains are available for use in diets, wheat and maize are the two main raw materials predominantly used worldwide [22–24]. In modern cultivars, the AME of wheat can be in the range of 13.5 to 15.8 MJ/kg DM and in maize between 14.5 and 16.3 MJ/kg DM [22–26]. The AME content is the main factor that determines the economic value of cereal for poultry. The AME of wheat is somewhat lower than maize, predominantly because wheat has a lower oil content and a greater proportion of total non-starch polysaccharides (NSP) than maize [27]. Feed constituents such as NSP can reduce nutrient and energy availability and are subsequently classified as antinutrients because they reduce the feeding value of those feedstuffs [23,28,29]. Greater NSP content in cereals, particularly wheat, are associated with higher intestinal digesta viscosity, which is also known to negatively impact available energy, nutrient availability and growth performance [30–32].

Research is therefore needed to determine available energy and nutrient utilization accurately and precisely, accounting for the complexity of antinutritional factors. The objectives of the present study were therefore to quantify the carcass fat and protein retention, and differences in the efficiency of carcass energy retention resulting from feeding broiler chickens diets containing either wheat, maize or graded levels of both as the major cereal ingredient. A further objective was to determine the AME of the four cereal levels and examine the relationship between AME supply from wheat and maize, and the efficiency of carcass energy retention.

2. Materials and Methods

2.1. Laboratory Analysis

Single batches of wheat and maize were obtained. The cereals were ground to pass a 4 mm screen. Dry matter (DM) was determined by drying in a force draft oven at 100 °C for 24 h. Crude protein (N × 6.25) in the samples was determined by the Kjeldahl method, using a Kjeltec 1035 Autoanalyzer (Perstorp Analytical, Hoganas, Sweden) [33]. Oil (as ether extract) was extracted with diethyl ether by the Soxhlet method (HT 1043 Extraction Unit, Perstorp Analytical, Hoganas, Sweden) [33]. The content of non-starch polysaccharides (NSP) was measured using the method proposed by Englyst and Cumming [27]. Colorimetric measurements were performed on a Beckman DU-640 Spectrophotometer (Beckman Instruments, Inc., Arlington Heights, IL, USA). Gross energy (GE) of the cereals was measured using a Parr isoperibol bomb calorimeter (Parr-6200, Parr Instruments Company, Moline, IL, USA). Water extract viscosity (in vitro) was measured as follows: 2 g of each cereal sample were soaked in a tube containing 4 mL distilled water (40 °C water bath) for 30 min. The tube was centrifuged (10,000× *g* for 2 min), left for 15 min at room temperature, then a 0.5 mL aliquot was taken from the liquid portion in each of the tubes. The viscosity of this supernatant was measured in centipoise (cP) units using a rotating cone and cup viscometer (model DV-II þ LV, Brookfield, Stroughton, MA, USA).

2.2. Bioassays

Two experiments were conducted at the National Institute of Poultry Husbandry (NIPH), Harper Adams University. Four cereal samples were used in the experiments. Ground wheat and maize samples were used. Two additional dietary samples were produced by blending 333 g/kg ground maize with 667 g/kg ground wheat or 333 g/kg ground wheat with 667 g/kg ground maize.

2.2.1. Apparent Metabolizable Energy

Apparent metabolizable energy was determined by a precision-feeding procedure that was adapted from the method described by McNab and Blair [34]. Twenty-four individually caged ISA Brown cockerels were kept in individual cages (0.6 m × 0.7 m floor area), at a constant house temperature of 16 °C with 16 h of light per day. The birds had previously been fed ad libitum with a nutritionally complete proprietary feed. All feed was removed on the first day of the bioassay, although the birds were allowed water ad libitum. After 24 h, each cockerel had 50 mL of a sucrose solution (600 g sucrose/L water) placed through a tube into its crop. After a further 24 h, 50 g of one of the four cereal samples was also placed into the bird's crop. Each cereal sample was randomly assigned to one of six replicate birds in a randomized block design. After a further 24 h, all birds were given 50 mL water by tube. The cockerel's droppings were collected for 48 h after feeding. The droppings were then dried at 60 °C before gross energy and nitrogen analysis. Apparent metabolizable energy was determined as the difference between gross energy intake and the gross energy in the droppings per kg of feed intake as previously described [35].

2.2.2. Carcass Energy Retention

Carcass energy retention from the four cereal samples was determined in broiler chickens from 7 to 21 days of age. A basal feed was formulated (Table 1). Previous studies [21] had indicated that this diet formulation was given to 7–21 day old broiler chickens.

Table 1. Ingredient composition of the basal diet for determination of broiler chicken carcass energy retention.

Ingredients (g/kg)	Control
Wheat	300
Maize gluten meal	33.3
Hulless soya bean meal	83.3
Full fat soya	433.3
Fish meal	83.3
Lysine HCl	3.33
Methionine	5.0
Dicalcium phosphate	25.0
Vitamin mineral premix [1]	33.33
Total	1000
Calculated analysis	
AME MJ kg^{-1} DM	13.2
Crude protein g kg^{-1} DM	342
Lysine g kg^{-1} DM	23.1
Methionine + cystine g kg^{-1} DM	15.1
Calcium g kg^{-1} DM	19.3
Phoshorus g kg^{-1} DM	12.2
Sodium g kg^{-1} DM	4.0

[1] The Vitamin mineral premix contained vitamins and trace elements to meet the requirements specified by NRC [36]. The major components were: Phosphorus 95 g kg^{-1}, methionine 50 g kg^{-1}, calcium 219 g kg^{-1}, sodium 30 g kg^{-1}, copper sulphate 0.5 g kg^{-1}, selenium 10 g kg^{-1}, retinol acetate 0.275 g kg^{-1}, cholecalciferol 625 mg kg^{-1}, alpha tocopherol 2.273 g kg^{-1}.

At 50% of ad libitum intake, the birds were healthy and had a slow growth rate. The basal feed was mixed with one of the four cereal samples (ground maize, ground wheat or two mixtures comprising different proportions of the two cereals (as described for the AME bioassay)). The basal feed and cereal mixture comprised of 50 parts basal feed added to 40 parts of the cereal sample.

One day old female Cobb 500 chicks were purchased from a commercial hatchery (Cyril Bason Ltd., Craven Arms, UK) and placed in a single floor pen for 5 days. All birds were fed a proprietary broiler starter feed during this period. After five days, birds were placed in cages and continued on the same feed for two further days. Feed and fresh water were provided ad libitum. At 7d of age, birds in the upper and lower quartiles of body weight were removed to reduce variation in the experimental material. The average body weight of broilers at this point was 0.149 kg (STDEV $\pm$ 0.0162), carcass dry matter of 0.260 g/kg and dry carcass gross energy of 24.98 MJ/kg. These obtained values were used to calculate the energy retention of 7d old birds at the beginning of the study.

Following randomization and blocking (spatial within cage tiers), two of the retained birds were placed into each cage (60 cages total). The birds were given a restricted amount of feed daily. For four of the treatment groups used for the determination of carcass energy retention when feeding cereal/blend samples, restriction was 90% of the previously determined birds' ad libitum feed intake (740 g for the 14d feeding period with increasing amounts allocated each day) [21]. Each bird therefore received feed that comprised 420 g basal feed and 320 g cereal/blend sample over the 14d feeding period. Chicks in the fifth treatment group (control group) were fed the basal feed alone with a daily amount determined to be a 50% restriction from *ad libitum* feed intake [21]. Each of these birds therefore received feed that comprised just 420 g basal feed over the 14d feeding period. For each carcass energy retention determination of each experimental treatment group, 12 cage replicates were used.

At the end of the feeding period all the birds were weighed and then killed by cervical dislocation. The whole carcasses of both birds from each cage, including feather, intestine, legs, head and beak, were ground, homogenized and sampled [21]. Following freeze-drying and milling of the samples, crude protein and crude fat (ether extract) were determined. Each bird in the experiment ate the same amount of basal feed (420 g over the 14d feeding period). The effect of the four different cereal samples on carcass energy retention was therefore described by determining the amount of carcass fat and protein retained in these birds (90% feed restriction) and deducting it from the carcass fat and protein retained by the mean of the birds fed the basal feed alone (50% feed restriction). Four dietary treatment groups were therefore compared. The total carcass energy retention (RE) was obtained as a difference in energy retained in the carcasses at 21d, adjusting for the values pertaining to the 7d old birds as previously measured using the equation below:

REf (MJ carcass) = REf 21d − REf 7d
REp (MJ carcass) = REp 21d − REp 7d
RE (MJ carcass) = [(REf 21d − REf 7d) + (REp 21d − REp 7d)]
REf (MJ)—energy retained as carcass fat at 21 and 7d, respectively (39.12 MJ/kg)
REp (MJ)—energy retained as carcass protein at 21 and 7d, respectively (23·6 MJ/kg)

The energy retention resulting from the additional intake of the test cereal only (REc) was then calculated using the following equation:

REc (MJ kg^{-1} cereal) = [(REf 90% − REf 50%) + (REp 90% − REp 50%)]/W
REf 90%—energy retained as carcass fat in birds fed at 90% restriction (39.12 MJ/kg)
REf 50%—energy retained as carcass protein in birds fed at 90% restriction (39.12 MJ/kg
REp 90%—energy retained as carcass protein in birds fed at 90% restriction (23.6 MJ/kg)
REp 50%—energy retained as carcass protein in birds fed at 50% restriction (23.6 MJ/kg)
REc (MJ)—energy retained in carcass attributed to cereal only
W—Amount (kg of dry matter) of the experimental cereal sample included in diets fed with 90% restriction

Efficiency of AME use for energy retention Kre = REc/AME intake.

The values 39.12 and 23·6 MJ/kg are GE values (constants) per kilogram of fat and protein, respectively, derived by Okumura and Mori [37].

2.3. Statistical Analyzes

The data were statistically analyzed using the general ANOVA procedure of Genstat (23rd edition, VSN International Ltd., Oxford, UK), in a randomized block design. Additionally, the effects of the four cereal/blend samples on determined AME and broiler chicken carcass energy deposition were partitioned into their linear and quadratic effects using orthogonal polynomial contrasts. In all instances, differences were reported as significant at $p < 0.05$ and trends were noted when the p value was $\geq$0.05 but <0.1. Data were checked for normality and homogeneity of residuals prior to parametric tests.

3. Results

The determined nutrient compositions of the wheat and maize samples are detailed in Table 2. Wheat samples had greater CP, less fat and a threefold increase in soluble NSP that was reflected in the higher in vitro viscosity values. There was a linear ($p < 0.001$) increase in AME with increasing amounts of maize within the four cereal mixtures, with the analysis indicating that the AME of maize was 1.4 MJ/kg (SE = 0.0568) greater than that of wheat (Table 3). Table 4 details cereal intakes and carcass composition of chickens fed the experimental diets. The birds in the broiler carcass energy retention experiment ate all feed that was offered each day. There were no ($p > 0.05$) differences in growth performance although the birds fed maize tended ($p = 0.074$) to have higher weight gains.

Table 2. Determined laboratory analysis of the wheat and maize samples *.

Laboratory Measurements	Wheat	Maize
Dry matter (g/kg^{-1})	855	857
Crude protein (N × 6.25) (g/kg^{-1} DM)	128	84
Crude fat (g/kg^{-1} DM)	21	33
Gross energy (MJ/kg^{-1} DM)	18.41	18.60
Total Non-Starch Polysaccharides (g/kg^{-1} DM)	106	82
Suluble Non-Starch Polysaccharides (g/kg^{-1} DM)	35	11
Viscosity (cP)	3.2	1.7

* All analyses were performed in technical duplicates.

Table 3. Determined apparent metabolizable energy (AME MJ/kg^{-1} DM) of four cereal samples (n = 6) for broilers.

Item	Wheat	Cereal Mixtures		Maize	SEM	Probability of Differences		
		0.67 Wheat 0.33 Maize	0.33 Wheat 0.67 Maize			*p*-Value	L	Q
AME	13.39	13.73	14.25	14.77	0.253	0.007	<0.001	0.731

SEM: pooled standard error of the mean; *p*-value: Fisher probability; L: linear response; Q: quadratic response.

Table 4. Cereal/blend intakes and carcass composition of chickens fed four cereal-based diets.

Item	Basal Feed	Basal + Wheat	Basal + 0.67 Wheat + 0.33 Maize	Basal + 0.33 Wheat + 0.67 Maize	Basal + Maize	SEM	*p*-Value *
Feed allocation	50% restrict	90% restrict	90% restrict	90% restrict	90% restrict	-	-
Basal feed intake of bird (kg of DM bird^{-1})	0.420	0.420	0.420	0.420	0.420	-	-
Test cereal intake of bird (kg of DM bird^{-1})	-	0.320	0.320	0.320	0.320	-	-
AME intake from test cereals (kg of DM bird^{-1})	-	4.28	4.39	4.56	4.73	-	-
Live weight of bird at 7d (kg bird^{-1})	0.150	0.150	0.153	0.147	0.145	0.0041	0.752
Carcass GE at 7d old (MJ kg^{-1} DM)	0.97	0.98	0.99	0.95	0.94	0.027	0.752
Live weight of bird at 21d (kg bird^{-1})	0.393	0.605	0.609	0.604	0.612	0.0045	0.074
Carcass GE at 21d old (MJ kg^{-1} DM)	21.10	24.04	24.28	24.54	24.86	0.107	0.074
Total carcass dry matter (g/g)	0.100	0.174	0.179	0.181	0.185	0.0015	0.276
Total carcass fat at 21d old (g bird^{-1})	2.12	4.19	4.34	4.46	4.60	0.045	0.131
Total carcass protein at 21d old (g bird^{-1})	73.2	105.4	103.8	104.2	102.2	0.922	0.321

AME: apparent metabolizable energy; DM: dry matter; GE: gross energy; MJ: megajoules; SEM: pooled standard error of the mean; *p*-value: Fisher probability; * The comparison does not include the values for the basal feed only.

Increasing proportions of maize resulted in linear increases in carcass fat and energy retained from fat ($p < 0.001$). There were also linear (L = 0.032) decreases in carcass protein and energy retained from protein, although these were not significant ($p = 0.121$) (Table 5). Overall, birds fed maize as a cereal source retained 18.1% more ($p < 0.001$) carcass energy than birds fed wheat, however, the determined AME of these two cereals indicated that the maize had a 10.5% greater AME concentration (Table 3). The efficiency of carcass energy retained (Kre) tended ($p = 0.060$) to increase with greater proportion of dietary maize in a linear fashion (L = 0.009) (Table 5).

Table 5. Derived carcass energy deposition attributable to the additional dietary cereal intakes (relative to birds fed basal feed only) of broiler chickens.

Item	Wheat	Cereal Mixture		Maize	SEM	Probability of Differences		
		0.67 Wheat 0.33 Maize	0.33 Wheat 0.67 Maize			*p*-Value	L	Q
Carcass fat from cereals (g bird^{-1})	32.7	38.6	40.4	44.1	0.11	<0.001	<0.001	0.320
Carcass GE from fat (MJ)	1.28	1.51	1.58	1.72	0.043	<0.001	<0.001	0.320
Carcass protein from cereals (g bird^{-1})	32.2	30.6	31.0	29.0	0.92	0.121	0.032	0.793
Carcass GE from protein (MJ)	0.76	0.72	0.73	0.68	0.022	0.121	0.032	0.793
Carcass GE from fat and protein (MJ)	2.04	2.23	2.31	2.41	0.052	<0.001	<0.001	0.353
RE (MJ kg^{-1} DM)	7.45	8.15	8.44	8.79	0.189	<0.001	<0.001	0.353
Kre	0.564	0.589	0.598	0.612	0.012	0.060	0.009	0.610

GE: gross energy; MJ: megajoules; RE: total carcass energy retained; Kre: efficiency of carcass energy utilization; SEM: pooled standard error of the mean; *p*-value: Fisher probability; L: linear response; Q: quadratic response.

4. Discussion

The chemical composition of the two cereal samples were in the expected ranges and similar to the mean of the feed wheat and maize samples [22,24,25,38–40]. The determined AME of the maize and wheat were also comparable to previously published data [22,24,25,38–40]. Increasing proportions of maize in the cereal mixtures gave a linear increase in the determined AME and this indicates that the AME contribution of the different cereals within the mixtures were additive. Dale and Fuller [41] and Hong et al. [10] also reported a satisfactory degree of additivity of metabolizable energy values for both cereals and high protein feeds.

The primary objective of this study was to examine whether there are differences in efficiency in the use of the AME provided by wheat and maize. Empirical [18] and modeling [19,20] data suggest that maize would have a higher efficiency of energy utilization since maize has a higher content of oil, which has a higher efficiency of utilization than carbohydrates or proteins [18]. In the present study, maize was confirmed to have a 1.4 MJ/kg advantage over wheat in AME. Wheat has a higher content of NSP and would be expected to increase the amount of intestinal bacterial fermentation [42,43]. Diets with a high NSP content can reduce the rate of feed passage which may influence gut development, increase in vivo digesta viscosity and encourage the proliferation of microflora in the small intestines [44–46]. Not only can such bacteria ferment and utilize carbohydrate and protein, therefore competing with the host for nutrients [47], but some species secrete enzymes that lead to deconjugation of bile acids resulting in an impairment of lipid digestion and absorption [48,49]. Furthermore, an increase in gut microflora proliferation may also increase the proportion of nutrients that are fermented within the lumen of the digestive tract, thus resulting in a higher heat increment of digestion and thus reducing the amount of dietary energy available for carcass energy retention. Muramatsu et al. [50] demonstrated that conventional chickens had an increased heat production relative to germ-free chickens because of their increased microbial proliferation. Different microbial profiles attributed to wheat and maize, due to differing NSP content and digesta viscosity, may therefore be important variables when modeling dietary retention. The age of the birds may also play an important role since the AME values obtained with broilers tended to be slightly lower than for roosters or poults [41,51]. Research with ad libitum fed broilers [51] also showed that metabolizable to digestible energy ratio was lowest at 7d of age and higher in birds fed on maize-based compared to those fed on wheat-based diets. Thus, further confirming the potential importance of dietary NSP and age of experimental birds.

The bioassay used in the present experiment contained one group of birds fed a restricted amount of basal feed and four other treatment groups that were given exactly the same amount of basal feed but supplemented with one of four additional straight cereals or mixtures. The additional carcass fat and protein retention could then be related directly to the additional nutrient supply of the four test mixtures. The restricted feeding method ensured that the feed intakes were as planned.

Research has found a negative relationship between dietary AME and its pentosan/NSP content [44,47,51–54], which was supported in this study. However, there was no significant effect of increasing maize levels/reduced NSP content on the Kre although there was a trend for a relatively small linear increase. The lack of a negative relationship between Kre and NSP was unexpected. However, the restricted feeding in this study may be a reason for the relatively low NSP intake, thus preventing possible impact on the rate of feed passage, in vivo digesta viscosity and microbial proliferation. The birds fed increasing amounts of maize, i.e., reduced dietary NSP, retained increasing amounts of carcass fat and numerically decreasing amounts of carcass protein. These birds had increasing AME intakes and so any energy intake above the bird requirements would have been deposited as fat. The ME:GE ratio of maize was 0.794 compared to 0.727 for wheat, which represents a 9.2% advantage for maize. The numerical reduction in the amount of carcass protein, whilst not significantly different, was not expected, even though the maize sample had less protein than the wheat sample. The basal feed was formulated (343 g/kg crude protein, with 67 g/kg CP of lysine and 44 g/kg methionine plus cystine) so that the overall diets did not limit the birds' abilities to deposit lean tissue. The total reduction in carcass protein was not large, as there was only a range of 3.2 g between the four dietary treatments, whilst there was a difference of 14 g (184 vs. 170 g/bird) in dietary crude protein intakes over the experimental feeding period. However, the experiment demonstrates that growing broiler chickens vary the relative proportions of carcass fat and protein deposition depending on the nutrient composition of their dietary energy supply. MacLeod [55] also demonstrated that the growing fowl responded to differences in dietary nutrient and energy intakes by varying the rate of energy deposition as fat and protein. Thus, it is important that nutritionists understand differences in energy deposition as fat and protein based on the cereals selected in dietary formulations.

5. Conclusions

The present study confirmed the energy utilization of maize and wheat for growing chickens. Furthermore, AME values of both cereals were confirmed to be additive. There were different AME intakes from feeding the different cereal samples, however, the efficiency in the use of energy for carcass energy retention only tended to be numerically higher, therefore not conclusively confirming or refuting an additive relationship for Kre. The information provided by this study can be used to improve models of energy utilization of different cereal sources for poultry. To further improve the practical diet formulations for broiler chickens, experiments with a wider variety of feedstuffs and comparison between different feeding techniques are needed.

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Data Availability Statement: The data that support the findings of this study are available on reasonable request from the corresponding author.

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