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EQUI-ENERGY REPLACEMENT OF NATIVE MAIZE WITH EXTRUDED MAIZE IN BROILER CHICKEN DIETS: EFFECT ON GROWTH PERFORMANCE, ENERGY UTILIZATION AND POST-PRANDIAL GLUCOSE RESPONSE

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ABSTRACT

The effect of equi-energy replacement of native maize with extruded maize on the growth performance, energy utilization indices and post-prandial glucose response of broiler chicken was investigated in a 42-day trial. A commercial flock of broiler chickens (n = 20,000) were offered either a "native" maize or extruded maize-soybean diet and monitored for growth performance: daily liveweight gain (DLWG), feed conversion ratio (FCR), flock uniformity and mortality during the pre-starter, starter, grower and finisher phases of production. One-day old chicks (n = 16) were slaughtered to obtain baseline data for the energy utilization study and another 32 chickens (16 chickens per treatment, 4 chickens per replicate) were slaughtered at 35-days post-hatch, and whole carcasses were processed. Another 80 chickens (40 chickens per treatment, 8 replicates per treatment and 5 chickens per replicate) were used for total tract excreta collection from 32−35 days post-hatch. At 42 days post-hatch, 32 fasted chickens (16 chickens per treatment) were sampled for blood 30 mins *pre-prandial* and 15, 30, 45, 60, 120, 180, 240 and 360 minutes *postprandial*, and plasma glucose was measured. Chickens fed extruded maize diets showed significantly improved FCR and flock uniformity across phases, while DLWG improvements were seen only in the pre-starter, grower and finisher phases. Metabolizable energy (ME) was significantly higher in the control group ($p = 0.03$), but energy retention as fat and protein, net energy of production, heat of production and efficiencies of ME used for energy retention and protein retention were unaffected. The extruded maize diet improved the efficiency of ME used for fat retention ($p = 0.03$). Postprandial plasma glucose concentrations were higher after 15 mins ($p = 0.00$) and 360 mins ($p = 0.00$), indicating enhanced starch digestibility.

Key words: feed processing; meat-type chicken; energy partitioning; glycaemic response; nutrient optimization

INTRODUCTION

Starch is the primary energy supply in conventional poultry diet formulations, making up about 40 % of the diet (Svihus, 2011; Zaefarian *et al.*, 2015), and is pre-dominantly delivered as cereal grains, either wheat or maize (Adeleye and Oladotun, 2020). Starch makes up about 71.1 % of the dry weight of maize (Bednar *et al.*, 2001), and while capacities for starch digestion, as much as 95 %, have been reported as ileal and total tract starch digestibilities in chickens (Zelenka and Čerešňáková, 2005; Aderibigbe *et al.*, 2020; Selle *et al.*, 2021). Less efficient starch digestion (< 95 %) has also been observed in studies involving both fast- and slow-growing broiler chickens (Adeleye *et al.*, 2020; Moss *et al.*, 2020) and are largely influenced by plant source (Moss *et al.*, 2020).

Variations in the structure of native starch granules and their amylose-amylopectin chain length distributions are often considered key to starch digestion (Li *et al.*, 2022, Zhu *et al.*, 2023). Exposure of starchy feedstuffs to a combination of high temperature, pressure and shear force during extrusion cooking initiates structural deformation of the starch granule in the form of swelling and rupture of the starch granule. Low moisture extrusion

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cooking particularly lends to gelatinization (formation of a homogenous "starch melt" phase) and fragmentation of amylose and amylopectin chains derived from the thermo-mechanical impact of the extruder screw (Pismag *et al.*, 2024), enabling increased surface area for interaction with digestive enzymes (Lai *et al.*, 2022) with resultant increases in starch digestive rates and glycaemic index *in vitro* (Lin *et al.*, 1997; Svihus *et al.*, 2005; Tran *et al.*, 2008; Li *et al.*, 2022). Extrusion cooking also denatures inherent anti-nutritional factors, such as α-amylase inhibitors (Zaefarian *et al.*, 2015). A wide-range of structural and physicochemical properties are exhibited by native starch of different plant origin (Adeleye *et al.*, 2016; Wang *et al.*, 2022), and these are known to influence their response to extrusion cooking. According to Li *et al.* (2022), extrusion cooking of cassava, potato, jackfruit seed and wheat starches improved their glycaemic index and digestive speed rate constant compared to their raw starches, however, these traits did not differ in raw versus extruded maize and rice starches.

The effect of extrusion cooking on starch digestibility has been investigated using the *post-prandial* glucose response protocol (Freire *et al.*, 1991), The *post-prandial* glucose response protocol is premised on the assumption that enzymatic starch digestion within the gastrointestinal tract produces glucose as a final product for absorption into the bloodstream, and significant success has been recorded in assessing *in vitro* and *in vivo* starch digestibility in response to different carbohydrate sources (Adeleye *et al.*, 2016; Lombardi *et al.*, 2020; Li *et al.*, 2022; Zhang *et al.*, 2023), glycaemic index (Kaur *et al.*, 2020), starch fractions (Giuberti *et al.*, 2012), thermal treatments (Hodges *et al.*, 2020) and other macronutrients in the matrix (Bell *et al.*, 2015), using this protocol.

While there exists a paucity of information on the effect of extrusion cooking on energy utilization indices in poultry, a few studies conducted in piglets and growing pigs report a significant effect of extrusion cooking on digestible energy and metabolizable energy of diets (Rodriguez *et al.*, 2020; Zhang *et al.*, 2022) and apparent ileal and total tract energy, nitrogen and starch digestibility (Freire *et al.*, 1991; Rodriguez *et al.*, 2020; Zhang *et al.*, 2022).

The current study investigated the equi-energy replacement of native maize with extruded maize in broiler chicken diets and its effect on starch digestion and energy utilization.

MATERIAL AND METHODS

The experimental protocols, adopted in this study, were reviewed and approved by the Department of Animal Science, University of Ibadan, Nigeria according to the guidelines for ethical conduct and reporting of animal research (Jarvis *et al.*, 2005; Kilkenny *et al.*, 2010).

Extrusion process

Whole maize grains were obtained from plant breeding stations in Katsina State (Northern Nigeria), ground in a hammer mill through a 6 mm screen mesh and analysed for proximate composition of crude protein, crude fat, crude fibre, ash, amino acids and phosphorus by near infrared reflectance spectroscopy (NIRS, Table 1). Thereafter, a half of the maize was processed through a single screw dry extruder (Insta-pro 2000 series VO1R02, Insta-Pro International, Grimes, Iowa, USA) with flow rate of 625 kg/h and extrusion temperature of 112 °C for 20 sec. The extruded maize was then allowed to cool down to room temperature. The unextruded corn was designated "native" maize and served as the control in this study.

Diets, animals and experimental design

Maize-soybean meal diets consisting of either native or extruded maize were formulated to meet breeder recommendations for Arbor acres (Aviagen, 2022). A four-phase feeding regimen − pre-starter (1 – 7 d), starter (8 – 16 d), grower (17 – 24 d) and finisher (25 – 35 d) – was adopted for this experiment (Tables 2 – 5). Prior to diet mixing, the extruded maize was re-ground through 6 mm- and 8 mm- sieves for the pre-starter and starter diets and the grower and finisher diets, respectively. The diets were offered as mash, and titanium dioxide was added to the diets as an indigestible dietary marker to enable digestibility evaluations.

Flock from a 35 d-broiler production cycle on a commercial farm in Nigeria were sampled for this study. A total of 20,000 day-old unsexed commercial broiler chicks (Arbor Acres) were housed in two barn style open-sided buildings (10,000 birds per barn, stocking density: 10 birds/m^2) about 50 m apart. Temperature was maintained at 32 °C during the first 7 days and, thereafter, an ambient temperature of 24 – 29 °C was maintained. Wood shaving was the bedding material of choice throughout the trial. Water and feed were offered *ad libitum*, and birds in each

Table 1. Chemical and nutritional composition of native and extruded maize used in the study

Ingredient	Native maize	Extruded maize
Dry matter, %	89.46	90.23
Apparent Metabolizable energy (kcal/kg)	3542.0	3499.0
Apparent Metabolizable energy corrected for nitrogen balance, AMEn (kcal/kg)	3434.0	3394.0
Crude protein (%)	7.98	9.31
Crude fat (%)	3.85	3.95
Crude fibre (%)	2.51	2.68
Ash (%)	1.33	1.31
Total Phosphorus (%)	0.25	0.22
Available phosphorus (%)	0.06	0.05
Lysine (%)	0.24	0.26
Digestible lysine (%)	0.20	0.22
Methionine (%)	0.17	0.17
Digestible methionine (%)	0.16	0.16
Cystine (%)	0.18	0.21
Digestible cystine (%)	0.17	0.21
Threonine (%)	0.29	0.36
Digestible threonine (%)	0.25	0.32
Tryptophan (%)	0.06	0.06
Digestible tryptophan (%)	0.05	0.05
Valine (%)	0.40	0.48
Digestible valine (%)	0.37	0.45
Isoleucine (%)	0.29	0.35
Digestible isoleucine (%)	0.28	0.34
Leucine (%)	0.96	1.23
Digestible leucine (%)	0.94	1.22
Phenylalanine (%)	0.37	0.46
Digestible phenylalanine (%)	0.37	0.47
Histidine (%)	0.23	0.26
Digestible histidine (%)	0.21	0.25
Arginine (%)	0.41	0.45
Digestible arginine (%)	0.39	0.43

barn were fed either of the dietary treatments. Bird weight was monitored at 7 d intervals throughout the study period with 20 birds weighed from 10 random locations in the building for each treatment, while feed intake was recorded as the feed delivered into the feeding system less the leftovers taken out. Mortality and unusual flock symptoms were also monitored.

Assessment of energy utilization

One-day old *post-hatch* chicks (n = 16) were weighed, killed by cervical dislocation and stored at -20 °C (with feathers, shanks, blood and all organs intact) until whole carcass analysis. At 28 d *post-hatch*, 80 broiler chickens (40 chickens per treatment) were randomly selected from the flock transferred into 148 cm × 96 cm × 116 cm metabolic cages (8 replicates, five birds per replicate) and acclimatized for 5 days, after which excreta were collected daily for 3 days. At 35-day old *post-hatch*, broiler chickens (n = 32;16 birds per treatment) were randomly selected from the flock, weighed, fasted for 2 hours before sacrificing to empty the gastrointestinal tract of undigested feed, killed by cervical dislocation and stored at -20 °C with feathers, shanks, blood and all organs intact until whole carcass analysis.

***Post-prandial* glucose response assay**

At 35 d *post-hatch*, another 32 broiler chickens were randomly transferred from the flock (16 chickens per treatment, 8 replicates, two birds per replicate)

Table 2. Ingredient composition, calculated nutrients and granulometry of broiler diets: pre-starter (0 – 7 d)

Ingredient (g/kg)	Native maize diet	Extruded maize diet
Soyabean meal	392.93	371.84
Maize	527.84	547.48
Soy oil	26.04	25.80
Limestone	12.15	11.93
Dicalcium phosphate	19.96	20.75
Choline chloride (50 % SiO_2)	4.56	4.56
Sodium bicarbonate	3.17	3.47
Vitamin-mineral mix	2.50	2.50
Lysine HCl	3.60	4.19
DL-methionine	3.99	4.16
L-threonine	1.79	2.06
NaCl	1.37	1.16
Phytase	0.10	0.10
Total	1000	1000
Calculated analysis		
Metabolizable energy (kcal/kg)	2950.00	2950.00
Crude protein (%)	23.00	23.00
Crude fat (%)	5.61	5.66
Crude fibre (%)	3.72	3.74
Sugars (%)	3.70	3.57
Sugars + starch (%)	36.17	37.23
Calcium (%)	0.96	0.96
Available phosphorus (%)	0.48	0.48
Digestible methionine (%)	0.69	0.70
Digestible methionine + cysteine (%)	0.95	0.95
Digestible lysine (%)	1.28	1.28
Digestible threonine (%)	0.86	0.86
Granulometry, %		
> 2.8 mm	4.0	2.0
2.0 – 2.8 mm	11.0	9.0
1.0 – 2.0 mm	34.6	35.2
< 1.0 mm	50.4	53.8

Composition of vitamin-mineral premix per kg/diet: vitamin A, 12,000 IU; vitamin D_3, 5,000 IU; vitamin E, 80 mg; vitamin K_3, 4.0 mg; vitamin B_1, 5 mg; vitamin B_2, 9 mg; niacin, 70 mg; calcium pantothenate, 20 mg; vitamin B_6, 4.3 mg; vitamin B_{12}, 0.017 mg; choline chloride, 1700 mg; folic acid, 2.5 mg; biotin, 0.22 mg; manganese, 120 mg; iron, 20 mg; zinc, 120 mg; copper, 16 mg; iodine, 1.25 mg; cobalt, selenium, 0.3 mg. Smizyme Multigrain DSM N.V, Netherlands, included at 60 g/tonne of feed. Calculated analysis based on nutritional values of feed ingredients (Evonik, 2015).

into metabolic cages and acclimatized for 6 days. Thereafter, the *post-prandial* glucose response study was carried out at 42 d *post-hatch*. Following 12 hours, broiler chickens were sampled for 20 – 50 µL of blood from the wing vein to establish their baseline blood glucose. Thereafter, the experimental diets were offered for 30 min, and blood sampled after 15, 30, 45, 60, 120, 180, 240 and 360 min *post-prandial*. Glucose was measured using a glucometer (ACCUCHEK active, Roche Diagnostics GmbH, Mammheim, Germany).

Chemical analysis

The maize samples were analysed for proximate composition of crude protein, crude fat, crude fibre, ash, amino acids and phosphorus by near infrared reflectance spectroscopy (NIRS). AME and AMEn were estimated by the WPSA prediction equations (WPSA, 1989) and granulometry was assessed in an electric sieve shaker system.

The whole chicken carcass (feathers, shanks, blood and all organs) was individually processed by

Table 3. Ingredient composition, calculated nutrients and granulometry of broiler diets: starter (8 – 16 d)

Ingredient (g/kg)	Native maize diet	Extruded maize diet
Soyabean meal	355.17	332.28
Maize	572.80	594.11
Soy oil	24.29	24.04
Limestone	11.28	11.03
Dicalcium phosphate	17.32	18.17
Choline chloride (50 % SiO_2)	4.29	4.29
Sodium bicarbonate	2.86	3.19
Vitamin-mineral mix	2.50	2.50
Lysine HCl	3.00	3.64
DL-methionine	3.46	3.64
L-threonine	1.34	1.63
NaCl	1.59	1.36
Phytase	0.10	0.10
Total	1000.00	1000.00
Calculated analysis		
Metabolizable energy (kcal/kg)	3000.00	3000.00
Crude protein (%)	21.50	21.50
Crude fat (%)	5.51	5.57
Crude fibre (%)	3.60	3.62
Sugars (%)	3.49	3.35
Sugars + starch (%)	38.68	39.82
Calcium (%)	0.87	0.87
Available phosphorus (%)	0.44	0.44
Digestible methionine (%)	0.62	0.63
Digestible methionine + cysteine (%)	0.87	0.87
Digestible lysine (%)	1.15	1.15
Digestible threonine (%)	0.77	0.77
Granulometry, %		
> 2.8 mm	11.8	4.8
2.0 – 2.8 mm	19.8	14.4
1.0 – 2.0 mm	33.0	33.8
< 1. 0 mm	35.4	47.0

Composition of vitamin-mineral premix per kg/diet: vitamin A, 12,000 IU; vitamin D_3, 5,000 IU; vitamin E, 80 mg; vitamin K_3, 4.0 mg; vitamin B_1, 5 mg; vitamin B_2, 9 mg; niacin, 70 mg; calcium pantothenate, 20 mg; vitamin B_6, 4.3 mg; vitamin B_{12}, 0.017 mg; choline chloride, 1700 mg; folic acid, 2.5 mg; biotin, 0.22 mg; manganese, 120 mg; iron, 20 mg; zinc, 120 mg; copper, 16 mg; iodine, 1.25 mg; cobalt, selenium, 0.3 mg. Smizyme Multigrain DSM N.V, Netherlands, included at 60 g/tonne of feed. Calculated analysis based on nutritional values of feed ingredients (Evonik, 2015).

chopping and coarse grinding in an industrial blender. Aliquot portions were then dried in a forced air oven at 105 °C. Dried carcass samples were analysed for nitrogen and ether extractable fat by the Kjeldahl and Soxhlet extraction methods (AOAC, 2005) respectively, and gross energy – by bomb calorimetry using benzoic acid as a calibration standard (AOAC, 1995). Daily collection of excreta was pooled on replicate basis and dried in a forced air oven at 55 °C until constant weight. Feed and excreta were also analysed for nitrogen, ether extractable fat and gross energy by standard protocols, and titanium – by a spectrophotometric method using a known amount of titanium dioxide to prepare common-matrix standards (Short *et al.*, 1996).

Calculations and statistical analysis

Metabolizable energy, net energy of product (NEp), heat production (HP), metabolizable energy intake (MEI), energy retention as protein (RE_p) and fat (RE_f) and efficiencies of ME used for energy retention (K_{RE}), lipid

Table 4. Ingredient composition, calculated nutrients and granulometry of broiler diets: grower (17 – 24 d)

Ingredient (g/kg)	Native maize diet	Extruded maize diet
Soyabean meal	304.28	279.39
Maize	622.97	646.14
Soy oil	29.38	29.10
Limestone	10.38	10.11
Dicalcium phosphate	14.95	15.88
Choline chloride (50 % SiO_2)	4.02	4.02
Sodium bicarbonate	2.75	3.11
Vitamin-mineral mix	2.50	2.50
Lysine HCl	2.78	3.48
DL-methionine	3.15	3.35
L-threonine	1.07	1.38
NaCl	1.68	1.44
Phytase	0.10	0.10
Total	1000.00	1000.00
Calculated analysis		
Metabolizable energy (kcal/kg)	3100.00	3100.00
Crude protein (%)	19.50	19.50
Crude fat (%)	6.08	6.08
Crude fibre (%)	3.42	3.42
Sugars (%)	3.19	3.19
Sugars + starch (%)	41.40	41.40
Calcium (%)	0.78	0.78
Available phosphorus (%)	0.39	0.39
Digestible methionine (%)	0.57	0.57
Digestible methionine + cysteine (%)	0.80	0.80
Digestible lysine (%)	1.02	1.02
Digestible threonine (%)	0.59	0.59
Granulometry, %		
> 2.8 mm	27.6	13.6
2.0 – 2.8 mm	18.0	18.2
1.0 – 2.0 mm	25.0	30.6
< 1.0 mm	29.4	37.6

Composition of vitamin-mineral premix per kg/diet: vitamin A, 12,000 IU; vitamin D_3, 5,000 IU; vitamin E, 80 mg; vitamin K_3, 4.0 mg; vitamin B_1, 5 mg; vitamin B_2, 9 mg; niacin, 70 mg; calcium pantothenate, 20 mg; vitamin B_6, 4.3 mg; vitamin B_{12}, 0.017 mg; choline chloride, 1700 mg; folic acid, 2.5 mg; biotin, 0.22 mg; manganese, 120 mg; iron, 20 mg; zinc, 120 mg; copper, 16 mg; iodine, 1.25 mg; cobalt, selenium, 0.3 mg. Smizyme Multigrain DSM N.V, Netherlands, included at 60 g/tonne of feed. Calculated analysis based on nutritional values of feed ingredients (Evonik, 2015).

retention (K_{REf}) and protein retention (KREp) were estimated by the equations of Olukosi *et al.* (2008). The peak plasma glucose concentration (mg/dL), time at peak plasma glucose concentration (min) and area under the plasma glucose concentration-time curve (AUC, $mg/dL^{-1} \cdot 360\ min^{-1}$) were calculated for each bird using the PK Solver add-in in Excel (Zhang *et al.*, 2010). All data were subjected to descriptive statistics, means were compared using the Student t-test procedure (JASP v 0.18.2) and significance was based on a 5 % probability level.

RESULTS

No unusual flock symptoms were observed throughout the study period. The effects of equi-energy replacement of native maize with extrusion cooked maize in the diets of broiler chickens on the growth performance of broiler chickens in the pre-starter, starter, grower and finisher phases of this study are shown in Table 6.

Table 5. Gross composition, calculated and analysed nutrients and granulometry of broiler diets: grower (25 – 35 d)

Ingredient (g/kg)	Native maize diet	Extruded maize diet
Soyabean meal	279.41	279.39
Maize	635.15	646.14
Soy oil	42.48	29.10
Limestone	10.05	10.11
Dicalcium phosphate	14.36	15.88
Choline chloride (50 % SiO_2)	4.02	4.02
Sodium bicarbonate	3.12	3.11
Vitamin-mineral mix	2.50	2.50
Lysine HCl	3.50	3.48
DL-methionine	2.88	3.35
L- threonine	1.00	1.38
NaCl	1.44	1.44
Phytase	0.10	0.10
Total	1000.00	1000.00
Calculated nutrients		
Metabolizable energy (kcal/kg)	3200.00	3200.00
Crude protein (%)	18.50	18.50
Crude fat (%)	7.37	7.44
Crude fibre (%)	3.30	3.32
Sugars (%)	3.02	2.87
Sugars + starch (%)	41.96	43.23
Calcium (%)	0.75	0.75
Available phosphorus (%)	0.38	0.38
Digestible methionine (%)	0.53	0.54
Digestible methionine + cysteine (%)	0.75	0.75
Digestible lysine (%)	1.02	1.02
Digestible threonine (%)	0.64	0.64
Analysed nutrients		
Moisture (%)	10.92	10.54
Crude protein (%)	18.83	19.53
Crude fat (%)	3.86	4.11
Crude fibre (%)	4.68	4.55
Granulometry, %		
> 2.8 mm	35.2	12.0
2.0 – 2.8 mm	13.4	16.8
1.0 – 2.0 mm	20.0	28.6
< 1.0 mm	31.0	42.6

Composition of vitamin-mineral premix per kg/diet: vitamin A, 12,000 IU; vitamin D_3, 5,000 IU; vitamin E, 80 mg; vitamin K_3, 4.0 mg; vitamin B_1, 5 mg; vitamin B_2, 9 mg; niacin, 70 mg; calcium pantothenate, 20 mg; vitamin B_6, 4.3 mg; vitamin B_{12}, 0.017 mg; choline chloride, 1700 mg; folic acid, 2.5 mg; biotin, 0.22 mg; manganese, 120 mg; iron, 20 mg; zinc, 120 mg; copper, 16 mg; iodine, 1.25 mg; cobalt, selenium, 0.3 mg. Smizyme Multigrain DSM N.V, Netherlands, included at 60 g/tonne of feed. Calculated analysis based on nutritional values of feed ingredients (Evonik, 2015).

The daily liveweight gain of chickens was significantly improved by the inclusion of extrusion cooked maize in their diets in the pre-starter ($p < 0.001$), grower ($p = 0.04$) and finisher ($p = 0.04$) phases, but not in the starter ($p = 0.15$) phase. The same trends were observed for FCR (pre-starter ($p < 0.001$), starter ($p = 0.01$), grower ($p = 0.01$) and finisher ($p < 0.001$) phases) and flock uniformity (pre-starter ($p < 0.001$), starter ($p = 0.02$), grower ($p < 0.001$) and finisher ($p < 0.001$) phases). When the entire experimental

Table 6. Effect of equi-energy replacement of native maize with extruded maize on performance indices of broiler chickens

	Native maize	Extruded maize	Probability value
Pre-starter phase (1 – 7 d)			
Daily liveweight gain (g/day/bird)	20.06 ± 0.98[b]	21.34 ± 0.93[a] ↑ 6.38 %	< 0.001
Feed conversion ratio	1.05 ± 0.05[b]	0.98 ± 0.04[a] ↑ 6.67 %	< 0.001
Mortality, %	0.19 ± 0.07	0.21 ± 0.08	0.63
Coefficient of variation in flock, %	3.70 ± 0.06[b]	3.30 ± 0.06[a] ↑ 10.8 %	< 0.001
Starter phase (8 – 16 d)			
Daily liveweight gain (g/day/bird)	30.79 ± 3.40	32.07 ± 1.00	0.15
Feed conversion ratio	2.75 ± 0.69[b]	2.71 ± 0.67[a] ↑ 1.45 %	0.01
Mortality, %	0.05 ± 0.02	0.06 ± 0.02	0.28
Coefficient of variation in flock, %	6.40 ± 0.28[b]	4.10 ± 0.19[a] ↑ 35.9 %	0.02
Grower phase (17 – 24 d) Daily liveweight gain (g/day/bird)	62.62 ± 6.28[b]	65.93 ± 2.92[a] ↑ 5.29 %	0.04
Feed conversion ratio	1.42 ± 0.15[a]	1.52 ± 0.07[b] ↑ 7.04 %	0.01
Mortality, %	0.06 ± 0.02	0.05 ± 0.02	0.37
Coefficient of variation in flock, %	4.60 ± 0.43[b]	1.70 ± 0.18[a] ↑ 63.04 %	< 0.001
Finisher phase (25 – 35 d) Daily liveweight gain (g/day/bird)	47.12 ± 5.60[b]	53.63 ± 5.06[a] ↑ 13.8 %	0.04
Feed conversion ratio	2.03 ± 0.25[b]	1.93 ± 0.23[a] ↑ 4.93 %	< 0.001
Mortality, %	0.03 ± 0.01	0.04 ± 0.01	0.18
Coefficient of variation in flock, %	3.20 ± 0.45[b]	3.10 ± 0.51[a] ↑ 3.13 %	< 0.001
Overall (1 – 35 d) Daily liveweight gain (g/day/bird)	43.80 ± 1.20[b]	47.30 ± 1.21[a] ↑ 7.99 %	< 0.001
Feed conversion ratio	1.56 ± 0.04	1.55 ± 0.04	0.43
Mortality, %	0.08 ± 0.08	0.07 ± 0.07	0.72
Coefficient of variation in flock, %	4.20 ± 0.45[b]	2.80 ± 0.51[a] ↑ 33.33 %	< 0.001

[a,b] Means within the same row with different superscripts are significantly different, $p < 0.05$.

period was considered, i.e. 1 – 35 d *post-hatch*, the previously significant effects of equi-energy replacement of native maize with extrusion cooked maize on FCR mellowed out ($p = 0.43$), however significant improvements in daily liveweight gain ($p < 0.001$) and flock uniformity ($p < 0.001$) were sustained. Mortalities in the flock remained low all through the study period and were not significantly influenced by equi-energy replacement of native maize with extrusion cooked maize.

The effect of equi-energy replacement of native maize with extrusion cooked maize in the diets of broiler chickens on energy utilization response indices of 35 d *post-hatch* broiler chickens are shown in Table 7.

Body weight and metabolizable energy intake (p = 0.00) were higher in chickens fed the extruded maize diets. In contrast, the metabolizable energy of the diet (p = 0.03) and metabolizable energy, as a percentage of gross energy (p = 0.01), were significantly lower in this group compared to the control group. Also, whole carcass fat was higher in chickens of the control group (p = 0.01), while the efficiency of metabolizable energy used for fat retention – KRE_f, was higher (p = 0.03) in chickens on the extrusion cooked maize diet.

The effect of equi-energy replacement of native maize with extrusion cooked maize in the diets of broiler chickens on *post-prandial* glucose response variables of 35 d *post-hatch* broiler chickens are shown in Table 8.

Plasma glucose concentration was significantly higher in chickens on the extruded maize diet at time points of 15 min (p = 0.00) and 360 min (p = 0.00) *post-prandial*. While the area under the plasma glucose concentration-time curve, AUC and the time at peak plasma glucose concentration – t_{max}, were

Table 7. Effect of equi-energy replacement of native maize with extruded maize on energy utilization response indices in broiler chickens

	Native maize	Extruded maize	Probability value
Body Weight, g	1542.0 ± 4.62[b]	1775.0 ± 40.41[a]	0.00
Metabolizable energy of diet, kJ/g	13.77 ± 0.04[a]	13.57 ± 0.15[b]	0.03
Metabolizable energy intake, MJ	32.90 ± 0.09[b]	34.76 ± 0.31[a]	0.00
Metabolizable energy as a percentage of gross energy, %	88.66 ± 1.68[a]	86.97 ± 1.52[b]	0.01
Whole carcass protein, g/kg	478.63 ± 50.55	465.58 ± 72.13	0.72
Whole carcass fat, g/kg	237.83 ± 23.33[a]	155.73 ± 55.81[b]	0.01
Energy retained as protein, REp, MJ	17.41 ± 1.84	19.49 ± 3.16	0.20
Energy retained as fat, RE_f, MJ	14.01 ± 1.40	10.60 ± 3.95	0.07
Net energy of production, MJ	14.02 ± 0.16	15.05 ± 2.86	0.40
Heat of production, MJ	18.88 ± 0.15	19.70 ± 0.29	0.59
Efficiency of metabolizable energy used for energy retention, KRE	0.43 ± 0.01	0.43 ± 0.08	0.84
Efficiency of metabolizable energy used for protein retention, KREp	0.43 ± 0.04	0.30 ± 0.11	0.46
Efficiency of metabolizable energy used for fat retention, KRE_f	0.53 ± 0.06[b]	0.56 ± 0.09[a]	0.03

[a,b] Means within the same row with different superscripts are significantly different, $p < 0.05$.

Table 8. Effect of equi-energy replacement of native maize with extruded maize on the post-prandial glucose response variables of 35 d-old broiler chickens

	Native maize	Extruded maize	Probability value
Peak plasma glucose concentration, Cmax, mg/dL	300.81 ± 23.81[b]	324.00 ± 25.18[a]	0.01
Time at peak plasma glucose concentration, t_{max}, min	152.81 ± 149.52	209.06 ± 176.85	0.34
Area under the plasma glucose concentration-time curve $_{0-360 mins}$ ($\times 10^3$), AUC, $mg/dl^{-1} \cdot 360\ min^{-1}$	98.42 ± 6.63	100.80 ± 6.22	0.30

[a,b] Means within the same row with different superscripts are significantly different, $p < 0.05$.

not significantly influenced by the treatment diets, the peak plasma glucose concentration – C_{max}, was significantly higher in chickens on the extrusion cooked maize diet (p = 0.01).

DISCUSSION

This study attempted to investigate the impact of extrusion cooked maize-based diets on the performance, starch digestion and absorption mechanisms, and energy partitioning in broiler chickens. An equi-energy replacement strategy was used to formulate the experimental diets with the aim to correct biases for increased density streamlining any bias.

The potential of extruded grains to improve productivity and yield in broiler chickens is considered to stem from enhanced palatability and nutrient density, improved digestibility and feed efficiency, reduced mortality, denaturation of anti-nutritional factors and control of pathogens by the high temperature treatment characteristic of extrusion cooking (Plavnik and Sklan, 1995; Okelo *et al.*, 2006; Filipovic *et al.*, 2010; Nikmaram *et al.*, 2017; Risyahadi *et al.*, 2023). Reports on the effect of feeding extruded maize diets on feed intake are varied (Meyer and Bobeck, 2021; Risyahadi *et al.*, 2023) with the nutrient density of extruded maize used in the diet formulation dubbed the culprit. Many papers have also reported improved feed conversion and body weights in broiler chickens (Risyahadi *et al.*, 2023) at different phases of growth, as observed in this study. However, some studies reported a null or negative effect of extrusion cooked maize-based diets on body weights and feed conversion of broiler chickens (Ljubojevic *et al.*, 2011; Saensukjaroenphon *et al.*, 2022). The distinct differences in observed responses of broiler chickens to extrusion cooked maize in these studies may be attributed to the maize varieties used and the extent of starch gelatinization achieved by the extrusion cooking process, which depends on extrusion cooking conditions, such as pre-conditioning criteria, screw speed, shear force, extruder retention time and extruder temperature (Abd El-Khalek and Janssens, 2010; Ali *et al.*, 2017; Deng *et al.*, 2023).

Increase in the degree of gelatinization of starch in feeds has been alluded to influence pellet hardness and textural properties of feed, and may disrupt processes related to feed intake and feed preference (Deng *et al.*, 2023). Despite no mention of the impact of extrusion cooked grains on flock uniformity, a marked improvement in flock uniformity was observed in this study in response to the equi-energy replacement of native maize with extruded maize. This may be attributed to a more homogenous distribution of maize in the feed matrix and more uniform nutrient absorption attributable to extrusion cooking.

Poor flock uniformity is often associated with limited feed availability resulting in competition for feed, nutrient density of the feed and feed homogeneity (Çiftci and Ercan, 2003), all of which may amount to metabolic stress-induced fluctuations in energy balance (Zuidhof *et al.*, 2017). Besides mortality, flock uniformity is a major concern for poultry farmers with poor uniformity considered an indicator of poor performance with economic implications (Toudic, 2007) and uniformity associated with low mortalities in broiler flocks (Vasdal *et al.*, 2019). Extrusion of maize-based diets has been shown to improve energy utilization indices: apparent digestibility of gross energy, AME and AMEn in broiler chickens over groups fed an unextruded diet (Plavnik and Sklan, 1995). Conversely, a 13.14 % decrease in metabolizable energy of maize-based diet for broiler chickens was supported by extruded maize in the diet of 42-day-old broiler chickens (Amornthewaphat *et al.*, 2005).

The apparent metabolizable energy corrected to zero nitrogen retention – AMEn is the most commonly used measure of an ingredient's energy value (Barzegar *et al.*, 2020). However, the net energy of production – NEp is a more accurate and comprehensive energy measure as it takes into consideration the partitioning of metabolizable energy into growth and maintenance functions, as well as heat of increment of feeding (considered as waste energy). While studies have shown that the net energy of production index is sensitive to diet composition, enzyme supplementation and bird age in broiler chickens (Moftakharzadeh *et al.*, 2019; Olukosi *et al.*, 2008; Tay-Zar *et al.*, 2024), there is a lack of information on the response of NE indices to extrusion cooking.

Theoretically, extrusion cooking is presumed to support more efficient energy utilization for growth and maintenance, whilst reducing heat increment, however this study observed no effect of extrusion cooking on NE. Worthy of note, however, is the higher efficiency of metabolizable energy used for fat retention – KRE_f in chickens on the extruded maize diet, in this study, despite lower fat accretion compared to the control group, similar to earlier studies (Puvača *et al.*, 2014). While data supporting *post-prandial* plasma glucose, as an index of starch digestibility in extruded diets for poultry, is also limited, 24 h-*post-prandial* plasma glucose concentration was reportedly higher in 7-day-old chicks offered pelleted versus extruded corn-based diets. An extrusion cooking-associated increase in intestinal viscosity of digesta and resistant starch were deemed responsible for the lower plasma glucose concentration (Sousa *et al.*, 2021).

CONCLUSION

This study suggests that extruded maize, as an equi-energy replacement for native maize, improves growth performance and flock uniformity in broiler chickens. Contrary to expectations, however, this improvement in performance could not be explained by Net energy of production estimates derived from the comparative slaughter technique. On the other hand, *post-prandial* glucose response reflected higher glucose availability in the plasma, as a result of extruded maize in the diets of chicken.

AUTHOR'S CONTRIBUTIONS

Conceptualization: ADELEYE, O., BALOGUN, A.

Methodology: ADELEYE, O., BALOGUN, A.

Investigation: BALOGUN, A.

Data curation and supervision: ADELEYE, O., FADAYOMI, O.

Writing-original draft preparation: FADAYOMI, O.

Writing-review and editing: ADELEYE, O.

Project administration: ADELEYE, O.

All authors have read and agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

The data presented in this study are available on request from the corresponding author.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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