Poultry Science Journal
ISSN: 2345-6604 (Print), 2345-6566 (Online)
http://psj.gau.ac.ir

Impact of Feed Pelletization Techniques on Performance Metrics and True Metabolizable Energy in Broiler Chickens

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Poultry Science Journal 2026, 14(2): 169-178

Keywords
Pellet quality
Feed processing
Nutrient retention
Broiler performance
Metabolizable energy

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Article history
Received: August 26, 2025
Revised: June 18, 2026
Accepted: September 12, 2026

Abstract

This study investigated the influence of feed physical form mash, mechanical friction pelleting, and steam-conditioned pelleting on broiler growth performance, nutrient digestibility, and metabolizable energy values. A total of 150 Ross 308 broiler chicks were allocated to one of three dietary treatments over a 21-day period. All diets were formulated using a standard commercial grower formulation and processed into mash, mechanically pelleted (without steam), or steam-conditioned pelleted (85 °C) forms. Key parameters assessed included body weight, feed conversion ratio (FCR), pellet quality, apparent and true metabolizable energy (AME, TME), nitrogen-corrected energy values (AMEn, TMEn), and coefficient of total tract apparent retention (CTTAR). Broilers receiving steam-conditioned pellets exhibited significantly improved body weight gain and FCR compared to those fed mash or mechanical pellets ($P < 0.05$). However, mechanical pellets resulted in the highest AME, AMEn, TME, and TMEn values ($P < 0.001$). Both pelleting techniques enhanced pellet durability and reduced fine particles, though steam conditioning lowered pellet hardness. Nutrient digestibility was generally improved with pelleted diets, though ash retention was adversely affected. These findings suggest that pelleting improves energy and nutrient utilization in broilers, with mechanical pelleting showing superior energy recovery, while steam conditioning yields better growth performance. The results highlight the trade-offs between pellet processing methods and their implications for optimizing feed formulation strategies in broiler production systems.

Introduction

Feed processing techniques play a critical role in modern poultry nutrition by influencing physical characteristics, digestibility, and nutrient availability of diets. Pelleting, in particular, has become a cornerstone of broiler feed manufacturing due to its positive effects on feed intake, growth performance, and nutrient efficiency (Behnke, 1994; Abdollahi *et al.*, 2013). Among various pelleting methods, the thermal and mechanical processes involved such as steam conditioning and mechanical friction pelleting can exert distinct influences on pellet quality, metabolic energy recovery, and bird performance (Dozier *et al.*, 2001; Liu *et al.*, 2019). Steam conditioning involves subjecting feed mash to moisture and heat prior to mechanical compression, enhancing pellet durability and hygienic quality. However, prolonged heat exposure may degrade heat-sensitive nutrients and reduce energy density (Svihus *et al.*, 2004b; Abdollahi *et al.*, 2018). In contrast, mechanical friction pelleting without steam conditioning minimizes thermal degradation but may result in lower pellet integrity and digestibility (Amerah *et al.*, 2008; Behnke and Beyer, 2002). Understanding the balance between pellet quality and nutrient availability is essential for optimizing feed formulation in broiler production systems. Energy efficiency remains a central concern in broiler nutrition, with metabolizable energy (ME) being the most commonly used metric for evaluating dietary

Please cite this article as Bounmy Keohavong , Sang Jip Ohh. 2026. Impact of Feed Pelletization Techniques on Performance Metrics and True Metabolizable Energy in Broiler Chickens. Poult. Sci. J. 14(2): 169-178.

DOI:10.22069/psj.2026.24004.2400

energy content. Both apparent (AME) and true metabolizable energy (TME), along with nitrogen-corrected values (AMEn and TMEn), offer insights into feed energy utilization (McNab and Blair, 1988; Kluth and Rodehutscord, 2009). Recent studies have highlighted the impact of feed form on ME values and retention coefficients, emphasizing the need for more precise evaluation under different pelleting regimes (Liu *et al.*, 2020; Nguyen *et al.*, 2022).

Given the growing interest in feed efficiency and sustainable broiler production, this study aims to compare the effects of three feed forms mash, mechanical friction pelleting, and steam-conditioned pelleting on growth performance, pellet quality, and energy utilization in broilers. We hypothesize that while both pelleting methods improve nutrient digestibility, they differ in their impact on ME values and production outcomes.

Materials and Methods

Experimental diets

To evaluate the influence of feed processing methods on the chemical composition of broiler diets (Table 1), a commercially formulated mash diet was subjected to two different pelleting treatments and used as the test material in this study. The mash form served as the control, while the two treatment groups consisted of diets processed into pellets via mechanical friction and steam conditioning, respectively. The mechanical friction pellets were produced without steam conditioning. Mash diets were directly pelleted using a pellet mill (Model CPP020, Chia Tung Development Corp., LTD, Product No. K116, Taiwan, R.O.C), which had a manufacturing capacity of 275.55 kg/h. The pellet mill was equipped with a die ring featuring 4 mm diameter holes and a thickness of 45 mm. The pellet temperature was monitored at the die exit and reached approximately 60 °C.

Table 1: Composition and nutrient profile of basal diets for growing broilers

Ingredients	(%)
Corn	40.08
Soybean meal	28.56
Wheat meal	15.00
DDGS	4.00
Wheat gluten	2.00
Rapeseed meal	2.00
Tallow	4.24
Limestone	1.50
Mono Dicalcium Phosphate (MDCP: 18/21)	1.12
Salt	0.28
DL - Methionine	0.31
Choline chloride (50 %)	0.16
L – Lysine (98 %)	0.44
Threonine (98.5 %)	0.06
Vitamin premix[1]	0.10
Mineral premix[2]	0.10
Clinacox	0.05
Chemical composition	
Moisture	11.18
Metabolizable energy (Kcal/kg)	3,126
Protein	21.00
Fat	7.96
Fiber	3.72
Ash	5.44
Calcium	0.90
Phosphorus	0.61
Lysine	1.35
Methionine	0.64
Methionine + Cystine	1.00
Available Phosphorus	0.46

[1] The vitamin premix contains the followings per kg of diet: Vitamin A, 18,000 IU; Vitamin D_3, 4,500 IU; Vitamin E, 31.5 IU; Menadione (K3), 3.6 mg; Thiamin (B1), 1.8 mg; Riboflavin (B2), 4.8 mg; Pyridoxine (B6), 3.6 mg; Cobalamin (B12), 0.03 mg; Niacin (B3), 22.5 mg; Pantothenic acid (B5), 15mg; Folic acid (B9), 0.45 mg.

[2] The mineral premix contains the followings per kg of diet: Mn,86.4 mg; Zn, 72 mg; Fe, 74.6 mg; Cu, 6 mg; I, 1.5 mg; Co, 0.29 mg; Se, 0.22 mg.

For the steam-conditioned pellets, the mash diets were first conditioned using a steam conditioner (capacity: 100 kg) at 85 °C for 10 minutes. The steamed mash was then immediately transferred to the same pellet mill used for mechanical pelleting, operating at a slightly higher capacity of 278.77 kg/h.

All feed processing was performed at the Kangwon National University (KNU) Feed Mill exactly one day prior to the start of the feeding trial to ensure diet freshness. Considering the feeding behavior and anatomical limitations of young broilers particularly their reduced ability to consume large particles both types of pelleted diets (mechanical and steam-conditioned) were subsequently crumbled using a 2–3 mm sieve before feeding to the birds.

Pellet Quality Evaluation

The physical quality characteristics of pellets produced by mechanical friction pelleting and steam-conditioned pelleting were evaluated by determining production rate, sifted pellet percentage, sifted fine percentage, bulk density, pellet hardness, and pellet durability index (PDI).

Pellet production rate was calculated as the quantity of pellets produced per hour (kg/h) during the pelleting process. The proportion of sifted pellets (%) and sifted fines (%) was determined by sieving representative pellet samples through a standard sieve and expressing the weight of retained pellets and fines as a percentage of the total sample weight. Bulk density (kg/m³) was determined by weighing pellets occupying a known volume and calculated as the ratio of pellet weight to container volume.

Pellet Hardness Measurement

Pellet hardness was determined using a Handpi Manual Test Stand Analyser equipped with a Digital Force Gauge (Model HLD, Yueqing Handpi Instruments Co., Ltd., China), following the method described by Svihus *et al.* (2004a). For each treatment, 30 pellets were randomly selected and individually positioned between the instrument's pressure piston and a fixed steel bar. A gradually increasing compressive force was applied until pellet fracture occurred. The maximum force required to break each pellet was recorded in Newtons (N) and used as an indicator of pellet hardness.

Pellet Durability Test

Pellet durability was evaluated according to the standard and modified procedures of the American Society of Agricultural Engineers (ASAE, 1997). Pellet samples were initially sieved using a No. 6 ASTM sieve to remove fines. A 500-g subsample of intact pellets was then placed in a dust-tight tumbling chamber (5 × 12 × 12 inches) fitted with a diagonally mounted baffle plate (2 × 9 inches). The chamber was rotated at 50 rpm for 10 min. Following tumbling, pellets were re-sieved using the same ASTM sieve, and the remaining intact pellets were weighed. Pellet durability was expressed as Pellet Durability Index (PDI), calculated as:

Equation 1

$$\text{PDI (\%)} = \frac{(\text{Weight of pellets after tumbling})100}{\text{Weight of pellets before tumbling}}$$

Higher PDI values indicate greater resistance of pellets to mechanical breakdown during handling, transportation, and storage.

Animals and housing conditions

A total of 150 one-day-old male broiler chicks (Ross 308) were obtained from a certified commercial hatchery and housed in electrically heated battery brooders. All chicks were fed a standard commercial starter diet for the first 10 days, following the nutritional guidelines of the National Research Council (NRC, 1994). On day 10, birds with similar body weights (average 216.73 g per bird) were selected, and ten birds were randomly allocated to each of 15 floor pens (65 cm height × 100 cm width × 120 cm depth), resulting in three dietary treatments with five replicate pens per treatment. Each pen was equipped with nipple drinkers, feed pans, and rice husk as bedding material. Feed and water were provided ad libitum throughout the study. Birds were raised under continuous lighting (24 h light/day) in a closed-sided broiler house. The ambient temperature was maintained at 31 °C on day 1 and gradually reduced to 22 °C by the end of the third week, following brooding recommendations by Aviagen (2019). The experiment was conducted over a 3-week period. Performance parameters recorded included initial and final body weight, body weight gain, feed intake, feed conversion ratio (FCR), and mortality. Feed intake, body weight gain, and FCR were adjusted for the body weight of any deceased birds during the trial to ensure accurate data representation, in accordance with standard performance trial procedures (Tucker, 1992).

Metabolic assay and evaluation of energy utilization

At the end of the 21-day feeding trial, eight broilers per dietary treatment with uniform body weights were selected and transferred to individual stainless-steel metabolism cages to evaluate nutrient digestibility and energy utilization. Birds were housed in pairs (two birds per cage), resulting in four replicates per treatment, and maintained under the same environmentally controlled conditions used during the feeding trial. To estimate endogenous nutrient and energy losses, an additional eight birds (two per treatment from the mash, mechanical friction pellet, and steam-conditioned pellet groups) were randomly selected and housed in the same manner. These birds served as unfed negative controls and received no feed during the excreta collection period. The evaluation of apparent metabolizable energy (AME), nitrogen-corrected AME (AMEn), true metabolizable energy (TME), nitrogen-corrected TME (TMEn), and the coefficient of total tract apparent retention

(CTTAR) followed the procedures described by Parsons (1985), with slight modifications to reduce handling stress and enhance the accuracy of feed intake and excreta collection. All birds included in the metabolism trial were fasted for 24 h prior to the administration of test diets, with water available ad libitum. Following the fasting period, birds in each treatment group were offered their respective experimental diets for 45 min, after which feed was withdrawn to ensure precise quantification of intake. Birds in the negative control group remained fasted throughout the 48-h collection period. Excreta were collected quantitatively over 48 h, immediately stored at −80 °C, and later freeze-dried, weighed, and finely ground for subsequent chemical analysis. Nutrient composition, nitrogen content, and gross energy of the excreta were determined to accurately calculate metabolizable energy values and nutrient retention indices.

Metabolizable energy and coefficient of nutrient retention

The metabolizable energy values namely apparent metabolizable energy (AME), nitrogen-corrected AME (AMEn), true metabolizable energy (TME), and nitrogen-corrected TME (TMEn) were calculated using the equations established by Sibbald (1976). In addition, nitrogen and energy balance were evaluated, and the coefficient of total tract apparent retention (CTTAR) was calculated for each nutrient to assess overall nutrient utilization efficiency.

Energy and nitrogen balance calculations

Gross energy intake (EI) and gross energy output (EO) were measured from the test ingredients and excreta, respectively. The metabolizable energy values were calculated using the following equations:

Equation 2

$$\text{AME (kcal/kg)} = \frac{(\text{EI} - \text{EO})}{\text{FI}}$$

Equation 3

$$\text{AMEn (kcal/kg)} = \text{AME} - \frac{8.22(\text{ANR})}{\text{FI}}$$

Equation 4

$$\text{TME (kcal/kg)} = \text{AME} + \frac{(\text{FEL})}{\text{FI}}$$

Equation 5

$$\text{TMEn (kcal/kg)} = \text{TME} - \frac{8.22(\text{ANR})}{\text{FI}} - \frac{8.22(\text{FNL})}{\text{FI}}$$

Where:

- EI = gross energy intake (kcal)
- EO = gross energy excreted (kcal)
- FI = feed intake (g; standardized to 30 g/bird)
- ANR = apparent nitrogen retained (g), calculated as nitrogen intake minus nitrogen output
- FEL = fasting energy loss (kcal)
- FNL = fasting nitrogen loss (g)

The factor 8.22 kcal/g N was applied for nitrogen correction based on the conversion proposed by Hill and Anderson (1958).

Nitrogen retention

Nitrogen retention was calculated to assess the efficiency of protein utilization:

Equation 6

$$\text{Apparent Nitrogen Retained (ANR)} = \text{N intake (g)} - \text{N output (g)}$$

Equation 7

$$\text{True Nitrogen Retained (TNR)} = \text{ANR} + \text{N excreted by fasted roosters (g)}$$

CTTAR and derived nutrients

The coefficient of total tract apparent retention (CTTAR) was used to evaluate nutrient utilization, calculated as:

Equation 8

$$\text{CTTAR} = \frac{(\text{Total nutrient ingested} - \text{Total nutrient excreted})}{\text{Total nutrient ingested}}$$

CTTAR values were determined for dry matter (DM), gross energy (GE), nitrogen (N), crude protein (CP), ether extract (fat), ash, organic matter (OM), and total carbohydrates (CHO). Organic matter was calculated (Kawauchi *et al*. 2011) as:

Equation 9

$$\text{OM} = \text{DM} - \text{Ash}$$

Total carbohydrate content was estimated as: \

Equation 10

$$\text{CHO} = \text{DM} - (\text{CP} + \text{Fat} + \text{Ash})$$

The method for calculating CTTAR was adopted from Zhang *et al*. (2011), and all nutrient retention metrics were expressed as proportions.

Chemical analysis

The chemical composition of the experimental diets and excreta was determined following standard protocols. All ground samples were analyzed in triplicate for moisture, ash, ether extract, gross energy, and nitrogen content in accordance with the methods described by the Association of Official Analytical Chemists (AOAC, 2005). Moisture content was determined by oven-drying 1 g of each sample at 105 °C for 5 hours. Ash content was measured by incinerating 1 g of each sample in a muffle furnace (Furnace 62700) at 550 °C for 5 hours. Ether extract (crude fat) was analyzed using a Soxhlet extraction system (Soxtest analyzer, Raypa®, Spain). Gross energy content was quantified using an adiabatic oxygen bomb calorimeter (Model 1261, Parr Instrument Company, USA). Nitrogen concentration

was determined using a Kjeltec nitrogen analyzer (Model 2300, Foss Tecator, Sweden), and crude protein (CP) was calculated by multiplying the nitrogen value by 6.25.

Statistical analysis

The experimental design consisted of three dietary treatments, with birds randomly assigned according to a completely randomized design (CRD). For the growth performance trial, each pen was treated as an experimental unit, while in the metabolism study, each metabolic cage represented a single experimental unit. Data were subjected to analysis of variance (ANOVA) using the General Linear Model (GLM) procedure of SAS software (version 9.1.2, SAS Institute Inc., Cary, NC, USA) (SAS Institute, 2004). When significant effects were detected ($p < 0.05$), Duncan's multiple range test was used to determine differences among treatment means (Duncan, 1955). Results were considered statistically significant at $p < 0.05$.

Results

The physical processing method significantly influenced multiple pellet quality attributes (Table 2). Steam conditioning pellets exhibited a higher production rate compared to those produced by mechanical friction alone ($P < 0.001$), indicating enhanced throughput under thermal conditioning. The proportion of sifted pellets was significantly greater in steam-conditioned diets, while the proportion of sifted fines was significantly lower than in the mechanically processed group ($P < 0.001$ for both). This suggests improved pellet integrity and reduced particle breakdown with steam conditioning. Although bulk density was slightly lower in steam-conditioned pellets, the difference was statistically significant ($P < 0.001$), likely due to increased porosity from heat and moisture expansion. Pellet hardness was significantly affected by processing method ($P < 0.05$), with mechanically pressed pellets demonstrating higher resistance to compression. Despite this, pellet durability index (PDI) was significantly higher in steam-conditioned pellets ($P < 0.001$), highlighting their superior resilience to mechanical stress during handling.

The physical form (Table 3) of the diet significantly influenced all evaluated nutrient composition parameters ($P < 0.001$). Steam-conditioned pellets had the highest dry matter content, followed by mechanically pressed pellets and mash diets. This pattern was also observed for gross energy (GE), where pelleted forms especially those produced via mechanical friction had significantly higher energy densities than the mash diet. Dietary crude protein and nitrogen contents were significantly increased in both pelleted diets compared to mash, with steam-conditioned pellets maintaining slightly lower values than mechanical friction pellets, though still significantly higher than mash. Interestingly, the fat content was significantly higher in mash compared to pelleted diets ($P < 0.001$), indicating potential fat loss or redistribution during pelleting. Conversely, ash content was significantly lower in pelleted diets than mash, possibly reflecting concentration effects due to moisture loss or reduced contamination during processing. The organic matter (OM) and total carbohydrate (CHO) contents were significantly greater in pelleted diets, particularly in the steam-conditioned group.

Table 2: Effects of mechanical friction and steam conditioning pelleting on physical quality characteristics of broiler feed pellets

Parameters	Pellet processing[1]		SEM[2]	P-values
	Mechanical friction	Steam conditioning		
Production rate (kg/h)	275.55	278.77	3.24	<0.001
Sifted pellet (%)	77.40	81.89	0.51	<0.001
Sifted fine (%)	22.05	17.76	0.48	<0.001
Bulk density (kg/m^3)	677.04	661.19	16.02	<0.001
Pellet hardness (*Newton*)	21.69	19.69	6.18	0.032
Pellet durability index (%)	93.34	95.13	1.40	<0.001

[1] Mechanical friction pellets were produced without steam conditioning. Steam-conditioned pellets were conditioned at 85°C before pelleting.
[2] SEM: Standard error of the mean (n = 20).

final weight ($P < 0.05$). A similar trend was observed for body weight gain (BWG) and average daily gain (ADG), both of which were significantly higher in the steam-conditioned group compared to mechanical friction and mash diets ($P < 0.05$). Feed intake (FI) and average daily feed intake (ADFI) were significantly higher in the mechanical friction group than in the steam-conditioned group ($P < 0.05$), The physical form of the diet significantly influenced the growth performance parameters of broiler chickens (Table 4). While initial body weight (BW) was similar across all groups ($P > 0.05$), differences became evident by the end of the trial period. Broilers fed the steam-conditioned pellet diet achieved the highest final BW, followed by the mash group, while those on mechanical friction pellets had the lowest

0.001). Furthermore, mortality rates were significantly higher in the mechanical friction group ($P < 0.01$), while the mash and steam-conditioned groups showed similarly low mortality.

although mash-fed birds had intermediate values. Despite lower feed intake, birds fed steam-conditioned pellets demonstrated the most efficient feed-to-gain ratio (F/G), with significantly better feed conversion compared to both other groups ($P <$

Table 3: Effects of dietary physical form on proximate nutrient composition of the experimental diets

Nutrients[1] (%)	Physical forms			SEM[2]	P-values
	Mash	Pellet			
		Mechanical friction	Steam conditioning		
Dry matter	87.63	89.80	90.40	0.16	<0.001
GE (Kcal/kg)	5467	5830	5666	6.04	<0.001
Protein	20.43	21.55	21.46	0.08	<0.001
Nitrogen	3.27	3.45	3.43	0.01	<0.001
Fat	7.50	7.06	7.15	0.10	<0.001
Ash	6.71	4.26	4.27	0.08	<0.001
OM	93.29	95.74	95.73	0.08	<0.001
Total CHO	52.98	56.93	57.52	0.18	<0.001

[1] Mash diet served as the control. Mechanical friction pellets were produced without steam conditioning. Steam-conditioned pellets were conditioned at 85°C prior to pelleting. Gross energy (GE), organic matter (OM), and total carbohydrates (CHO) were determined as described in the Materials and Methods.
[2] SEM = standard error of the mean (n = 15).

Table 4: Growth performance parameters of broiler chickens as affected by dietary physical form

Parameters[1]	Physical forms			SEM[2]	P-values
	Mash	Pellet			
		Mechanical friction	Steam conditioning		
Initial BW (g)	216.73	216.73	216.73	11.72	0.99
Final BW (g)	1237.36	1172.90	1270.93	128.39	0.032
FI (g)	1639.29	1679.89	1589.86	115.97	0.041
ADFI (g)	78.06	79.99	75.71	5.53	0.038
BWG (g)	1020.86	959.90	1049.93	132.19	0.036
ADG (g)	48.61	45.71	50.00	6.29	0.039
Feed/Gain	1.63	1.76	1.53	0.17	<0.001
Mortality (%)	0.40	0.80	0.40	0.47	0.018

[1] Mash diet served as the control. Mechanical friction pellet was produced without steam conditioning. Steam-conditioned pellet was produced using high-temperature steam conditioning (85 °C) prior to pelleting. FI: feed intake; ADFI: average daily feed intake; BWG: body weight gain; ADG: average daily gain.
[2] SEM: Standard error of the mean (n = 15).

The physical form of the experimental diets significantly influenced both total nutrient intake and the coefficient of total tract apparent retention (CTTAR) values for most parameters (Table 5). Broilers fed the mechanical friction pellet diet showed the highest intake of dry matter (DM), gross energy (GE), protein, nitrogen, fat, organic matter (OM), and carbohydrates ($P < 0.001$). Steam-conditioned pellet diets resulted in intermediate or lower intake levels for most nutrients, while mash diets generally produced significantly lower intake values, except for ash, which was highest in the mash group ($P < 0.001$). With respect to nutrient retention, CTTAR values for DM and GE were significantly higher in the mechanical friction group compared to mash and steam-conditioned treatments ($P < 0.001$). Fat retention was highest in both pellet diets, with no difference between mechanical friction and steam conditioning, but significantly greater than mash ($P <$ 0.001). Interestingly, protein and nitrogen retention were significantly lower in the steam-conditioned group compared to the other treatments ($P < 0.001$), while ash retention showed a stark decline from mash to steam-conditioned pellets, with the latter group demonstrating a negative retention value ($P < 0.001$), indicating substantial mineral excretion. Carbohydrate retention was slightly but significantly lower in both pellet groups compared to mash ($P <$ 0.001), although OM retention remained statistically unchanged among treatments ($P > 0.05$).

The physical form of the diet significantly affected digestibility and nutrient retention in broilers (Table 6). Dry matter digestibility (DMD) was highest in birds fed mechanical friction pellets, followed closely by mash, and was significantly lower in those fed steam-conditioned pellets ($P < 0.0001$), indicating a reduction in digestibility with high-temperature processing. Nitrogen intake and gross energy (GE) intake were significantly higher in the mechanical friction pellet group compared to mash and steam-

conditioned groups ($P < 0.001$), reflecting increased nutrient consumption. Despite higher intake, nitrogen output was also significantly elevated in both pellet groups compared to mash ($P < 0.001$), suggesting greater excretion or reduced nitrogen utilization efficiency. In terms of energy output, steam-conditioned diets resulted in significantly higher GE output than either mash or mechanical friction diets ($P < 0.05$), indicating less efficient energy retention. Both apparent nitrogen retention (ANR) and true nitrogen retention (TNR) were significantly improved in broilers fed mechanical friction pellets compared to other treatments ($P < 0.001$), demonstrating better protein utilization with moderate thermal processing.

Table 5: Total nutrient intake and apparent total tract retention coefficients of broiler chickens fed diets with different physical forms

Nutrients[1]	Mash	Pellet		SEM[2]	P-values
		Mechanical friction	Steam conditioning		
Total nutrient intake					
DM (g)	33.84	37.87	31.75	3.07	<0.001
GE (Kcal)	185.12	220.74	193.79	0.15	<0.001
Protein (g)	6.92	8.16	6.82	0.65	<0.001
Nitrogen (g)	1.11	1.31	1.09	0.10	<0.001
Fat (g)	2.54	2.68	2.27	0.22	<0.001
Ash (g)	2.27	1.61	1.36	0.15	<0.001
OM (g)	31.58	36.25	30.39	2.92	<0.001
CHO (g)	22.12	25.42	21.31	2.05	<0.001
The coefficient of total tract apparent retentions ($CTTAR_s$) values					
DM	0.83	0.84	0.80	0.02	<0.001
GE	0.85	0.87	0.85	0.01	<0.001
Protein	0.70	0.70	0.67	0.03	<0.001
Nitrogen	0.70	0.70	0.67	0.03	<0.001
Fat	0.94	0.96	0.96	0.004	<0.001
Ash	0.29	0.15	-0.80	0.08	<0.001
OM	0.87	0.87	0.87	0.01	0.87
CHO	0.93	0.91	0.91	0.01	<0.001

[1] Mash diet served as the control. Mechanical friction pellet was prepared without steam conditioning. Steam-conditioned pellet was produced using high-temperature steam conditioning (85 °C) prior to pelleting. DM: dry matter; GE: gross energy; OM: organic matter; CHO: total carbohydrates. All nutrient intake and apparent total tract retention values were determined on a per assay period basis (48 h metabolism assay) following Parsons (1985). CTTARs: coefficient of total tract apparent retention (unitless ratio).
[2] SEM: Standard error of the mean (n = 15).

Table 6: Apparent dry matter digestibility, nitrogen utilization, and energy balance of broiler chickens fed diets with different physical forms

Parameters[1]	Physical forms			SEM[2]	P-values
	Mash	Pellet			
		Mechanical friction	Steam conditioning		
DMD (%)	82.68	83.55	80.03	1.46	<0.001
N intake (g)	1.11	1.31	1.09	0.10	<0.001
GE intake (Kcal)	185.12	220.74	193.79	0.15	<0.001
N output (g)	0.34	0.39	0.39	0.03	<0.001
GE output (Kcal)	28.41	28.29	29.75	2.42	0.023
ANR (g)	0.77	0.92	0.78	0.03	<0.001
TNR (g)	1.11	1.26	1.13	0.03	<0.001

[1] Mash diet served as the control. Mechanical friction pellet was prepared without steam conditioning. Steam-conditioned pellet was produced using high-temperature steam conditioning (85 °C) prior to pelleting. DMD: dry matter digestibility; N: nitrogen; GE: gross energy; ANR: apparent nitrogen retained; TNR: true nitrogen retained. All intake, output, and retention values were determined on a per assay period basis (48 h metabolism assay) following Parsons (1985).
[2] SEM: Standard error of mean (n = 15).

Dietary physical form significantly influenced energy excretion and metabolizable energy utilization in broilers (Table 7). Energy excretion (EE) was highest in birds fed mash diets, followed by mechanical friction pellets, and was lowest in those receiving steam-conditioned pellets ($P < 0.0001$), indicating more efficient energy use in processed diets. All metabolizable energy parameters apparent metabolizable energy (AME), AME corrected for nitrogen (AMEn), true metabolizable energy (TME), and TME corrected for nitrogen (TMEn) were significantly higher in birds fed mechanical friction pellets compared to both steam-conditioned and mash diets ($P < 0.001$). Birds on steam-conditioned diets

had intermediate ME values, while mash-fed birds exhibited the lowest metabolizable energy values across all indices.

Table 7: Energy excretion and metabolizable energy values of broiler chickens fed diets with different physical forms

Parameters[1]	Physical forms			SEM[2]	P-values
	Mash	Pellet			
		Mechanical friction	Steam conditioning		
EE (Kcal/kg)	3568	3385	3254	42	<0.001
AME (Kcal/kg)	3085	3312	3206	67	0.018
AME_n (Kcal/kg)	3084	3311	3205	67	0.019
TME (Kcal/kg)	3221	3458	3350	66	0.012
TME_n (Kcal/kg)	3220	3457	3348	66	0.011

[1] Mash diet served as the control. Mechanical friction pellet was produced without steam conditioning. Steam-conditioned pellet was produced using high-temperature steam conditioning (85 °C) prior to pelleting. EE: energy excretion; AME: apparent metabolizable energy; AMEn: nitrogen-corrected apparent metabolizable energy; TME: true metabolizable energy; TMEn: nitrogen-corrected true metabolizable energy. All energy variables were calculated on a dry matter basis over the 48 h metabolism assay period following Parsons (1985).
[2] SEM: Standard error of mean (n = 15).

Discussion

The present study evaluated the influence of different physical forms of broiler diets mash, mechanical friction pellet, and steam-conditioned pellet on performance, digestibility, nutrient retention, pellet quality, and metabolizable energy values. The findings consistently demonstrate that feed physical form significantly affects broiler productivity and energy utilization, aligning with previous studies that emphasize the critical role of feed processing in poultry nutrition and feed efficiency (Behnke, 1994; Briggs *et al*., 1999).

Broilers fed steam-conditioned pellets exhibited superior body weight gain (BWG) and feed conversion ratio (FCR) compared to those on mash or mechanically pelleted diets ($P < 0.05$), consistent with previous reports that steam conditioning enhances pellet palatability and starch gelatinization, improving feed intake and nutrient availability (Behnke, 1994; Briggs *et al*., 1999). However, despite better performance metrics, steam conditioning resulted in slightly lower metabolizable energy values than mechanical pelleting. This suggests that performance improvement was likely driven more by feed form and digestibility dynamics than by energy density alone.

Steam conditioning is known to enhance pellet physical quality by improving particle binding and reducing the generation of fines during feed handling and transportation. These effects are primarily attributed to the combined action of heat and moisture, which promote starch gelatinization and increase the cohesiveness of feed particles (Briggs *et al*., 1999). However, exposure to elevated temperatures and moisture may also alter the structural properties of pellets, potentially reducing pellet hardness due to changes in particle arrangement and internal matrix characteristics. Therefore, steam conditioning represents an important processing strategy for improving pellet quality, although its effects on pellet physical characteristics may vary depending on processing conditions.

Pelleting can influence the chemical and nutritional characteristics of broiler diets through enhanced feed homogenization, reduced ingredient segregation, and physical modifications of nutrients during processing. Previous studies have suggested that pelleting may improve the utilization of dietary energy and lipids by increasing nutrient accessibility and facilitating digestive processes (Kawauchi *et al*., 2011). In contrast, exposure to elevated temperatures during steam conditioning may alter nutrient availability through physicochemical changes, including protein denaturation and Maillard reactions, which can reduce nitrogen utilization when processing conditions become excessively severe (Hill and Anderson, 1958). Furthermore, thermal processing may affect mineral utilization and retention due to changes in nutrient interactions and digestibility within the gastrointestinal tract (Zhang *et al*., 2011). Collectively, these findings indicate that the nutritional consequences of pelleting depend on both the processing method and the intensity of thermal treatment.

Pelleting and thermal conditioning processes can markedly influence metabolizable energy utilization in broiler diets through their effects on nutrient availability, feed physical properties, and digestive efficiency. Improvements in energy utilization associated with feed processing have been widely documented and are generally attributed to enhanced nutrient accessibility, reduced feed wastage, and alterations in starch and protein structure that facilitate digestion (Sibbald, 1976). From an energy balance perspective, variations in excreta energy output are closely associated with differences in metabolizable energy efficiency, consistent with established principles of energy partitioning in

poultry nutrition (Parsons, 1985). However, the extent of thermal processing may also influence the balance between nutrient enhancement and heat-induced nutrient alterations, suggesting that processing intensity can differentially affect energy recovery efficiency. Accordingly, the relationship between pelleting method and metabolizable energy utilization should be interpreted in the context of optimizing both growth performance and nutrient efficiency, depending on production objectives.

This study confirms that feed form and processing technique significantly influence broiler productivity, pellet quality, and nutrient and energy utilization. While mechanical pelleting improves energy values, steam conditioning enhances growth performance and pellet durability. These findings are consistent with prior work on pelleting effects and support its strategic use in commercial broiler diets (Briggs *et al*., 1999; Kawauchi *et al*., 2011).

Conclusion

The present study demonstrates that feed physical form and pelleting technique significantly influence growth performance, pellet quality, nutrient digestibility, and energy utilization in broiler chickens. Steam-conditioned pellets improved body weight gain and feed conversion ratio, likely due to enhanced pellet integrity and palatability. Conversely, mechanically pelleted diets processed without steam yielded the highest metabolizable energy values (AME, AMEn, TME, TMEn), suggesting superior energy recovery and reduced heat-induced nutrient degradation. Both pelleting methods improved nutrient retention and dry matter digestibility compared to mash diets, although steam conditioning reduced nitrogen and ash retention. These findings underscore the trade-offs between growth performance and energy efficiency depending on processing severity. Overall, feed pelleting particularly when optimized for temperature and moisture conditions offers significant benefits for improving broiler productivity and feed utilization. Selection of the appropriate pelleting method should consider production goals, energy economics, and nutrient preservation.

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