# Effects of dietary energy levels on performance and carcass yield of 2 meat-type broiler lines housed in hot and cool ambient temperatures

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**ABSTRACT**  Two meat-type broiler lines, line A and line B were fed experimental diets from 22–42 d with objectives to determine the effects of dietary metabolizable energy (**ME**) levels on feed intake (**FI**), performance, body composition, and processing yield as affected by environmental grow-out temperatures. Two thousand fifty male chicks from line A and 2,050 male chicks from line B were reared in 90-floor pens, 45 chicks per pen utilizing primary breeder nutrition and husbandry guidelines for starter (1–10 d) and grower (11–21 d) phases. Experimental finisher diets consisted of 5 increasing levels of apparent nitrogen corrected ME (2,800, 2,925, 3,050, 3,175, and 3,300 kcal/kg set at 19.5% crude protein and 1.0% dLys at each level) to represent 80, 90, 100, 110, and 120% ME of Evonik AminoChick energy level giving $2 \times 5$ factorial design and were fed from 22–42 d. All other amino acid levels in diets were formulated to a fixed ratio of dLys level. There were nine replicate pens for each diet and each line. The experiment was conducted twice—once in hot season (barn averages: 77.55 °F and 86.04% RH) and another in cool season (barn averages: 69.91 °F and 63.98% RH) of the year. Results showed that FI and feed conversion ratios (**FCR**) decreased ($P < 0.05$) linearly ($R^2 = 0.9$) by 61.25 g and 0.073 units for every 10% increase in dietary ME for combined analysis of lines and seasons. The % fat mass of total body mass increased by 0.57%, whereas % protein mass decreased by 0.21% across ME levels ($R^2 > 0.9$). However, there was no difference ($P > 0.05$) in % weights (of live weight) for wings, breast filet, tenders, or leg quarters across ME levels for both lines except % fat pad that increased ($P < 0.05$) by 0.20% for each 10% increment in dietary ME level. Line B had higher cumulative FI, BW gain, % lean, and protein mass of body mass than line A in hot season ($P < 0.05$). Feed intake was not different between lines in cool season ($P > 0.05$), whereas higher BW and improved FCR were observed for line A. Line A had higher % fat mass in both seasons. In summary, performance and yield results as affected by dietary ME levels were line specific and were affected by grow-out seasons. The optimal dietary ME level for the ME range studied (2,800–3,000 kcal/kg) at a constant recommended amino acid level lies in determining the best performance and profitability indices by taking into account the grow-out production inputs and processing yield outputs.

Key words: energy levels, feed intake, body weight, feed conversion, body composition, yield

## INTRODUCTION

The genetic progress of broiler's productive traits such as growth rate and breast yield has been exponential in the past 2 decades (Fancher, 2014). The selection for increased growth rate has sustained the improved efficiency seen with broilers (Carre, 2014). Feed intake (**FI**) has fueled this increased growth rate as broilers show the capacity to physiologically process an increasing amount of nutrients on a daily basis. The FI of broilers was thought to be regulated by the energy concentration of the diet (Fisher and Wilson, 1974; Leeson et al., 1996), a concept that is still strongly held by many nutritionists (Leeson, 2012). There is ongoing research to understand factors that govern FI

of current broiler genetics such as the physiological ability of broilers to digest feed and dietary energy content (Marchini et al., 2016). Furthermore, Lemme (2005) showed that FI was regulated not only by dietary energy level but by the concentration of amino acids in the diet (balanced protein). Consideration in confounding factors such as amino acid levels (Delezie et al., 2010; Swennen et al., 2010; Classen, 2013; Maharjan et al., 2020a), energy levels (Dozier and Gehring, 2014; Maharjan et al., 2020b), and physical quality of the feed could further contribute to our understanding on what drives FI. More recently, Classen (2013) discussed the confounding factors that affect response of broilers to dietary energy such as broiler genotype and age, dietary ingredient and nutrient composition, feed form, environment, protein to energy ratio, etc. It was concluded that the energy level did not affect FI when confounding factors could be minimized and the energy level of diet needed to be determined based on the maximum protein accretion of the bird. In addition, no effect on FI was reported when birds were fed 80 and 90% of their amino acid requirement (Aviagen, 2007).

The broiler industry perceives that reducing the energy levels of the diets by 25–50 kcal/kg will not impact performance, and thus could reduce feed cost associated with high energy diet. Dozier III and Gehrin (2014) studied the effects of 6 dietary metabolizable energy (AMEn) levels ranging from 3,000 to 3,150 kcal/kg at 30 kcal difference between each diet on growth performance and reported no significant effects on body weight (BW), FI, and FCR. The study further showed the effect could be genotype specific. However, another study conducted in broilers housed in high ambient temperature showed the performance and yield benefits in treatment group fed 55 kcal/kg higher AMEn throughout the feeding phases (Zhai et al., 2014). Scant information is available exhibiting on how the differences in wider ranges (at 125 kcal/kg) in dietary energy levels affect on broiler FI and performance at different grow-out environmental conditions. In this present study, broilers were fed diets with increasing energy levels with same amino acid content and were evaluated for affecting performance and yield characteristics to understand what dietary energy density would be optimal for improved performance specific to broiler lines. Two modern meat-type broiler lines were used in the evaluation during their finishing feeding phase (22–42 d) in hot and cool season of the year. The standardized ileal feed amino acid digestibility and body composition changes (protein mass and fat mass) in these broiler lines were also evaluated due to the effects of dietary ME changes in both seasons.

## MATERIALS AND METHODS

### Birds and Husbandry

Two thousand twenty-five male chicks from line A and 2,025 male chicks from line B were placed in 90-floor pens (house 1 and house 2, 45 pens each house), 45 chicks per pen and reared under husbandry practices recommended by primary breeder guidelines. Both the lines utilized in the study were fast-growing current meat broiler lines. All procedures of bird care and handling followed University of Arkansas IACUC protocol #15048. This experiment consisted 2 study trials conducted once in the hot season (24-h grow-out environmental mean values during experimental feeding phase: ∼77.55 ℉ and 86.04% RH) and then repeated in cool season (24-hr grow-out environmental mean values during experimental feeding phase: ∼69.91 ℉ and 63.98% RH) of the year to represent higher and recommended grow-out ambient temperatures. Therefore, a total of 8,100 day-old chicks were used in the study. For hot season, line A and line B chicks were hatched from 33-week-old and 32-week-old hens, respectively. For cool season, line A and line B chicks were hatched from 36-week-old and 37-week-old hens, respectively. Ambient temperature and relative humidity recorded for both trials are reported in Figures 1A–1D.

### Experimental Diets and Design

Diets were formulated based on reported standardized ileal digestible (SID) amino acids and AMEn in accordance with Evonik AminoChick recommendation. Birds were fed a common starter feed from 0 to 10 d formulated to 3,030 kcal/kg and 1.27% digestible lysine (dLys) (Supplementary Tables 1 and 2). A common grower feed, fed from 11 to 21 d, was formulated to 3,080 kcal/kg and 1.09% dLys (Supplementary Tables 1 and 2). At 22–42 d, both broiler lines were placed on the 5 experimental diets (9 replicate pens for each diet and each line) with 5 increasing levels of AMEn (2,800, 2,925, 3,050, 3,175, and 3,300 kcal/kg set at 19.5% crude protein and 1.0% dLys at each level) to represent 80, 90, 100, 110, and 120% ME of typically recommended Evonik AminoChick nutrient guidelines for energy level giving $2 \times 5$ factorial design (Table 1 and Table 2). Amino acid levels in diets were kept constant in all treatment diets and were formulated to a fixed ratio of dLys level (Table 3). The analysis of AMEn involved analysis of gross energy, dry matter, and nitrogen in feed and excreta. Gross energy (GE) was determined with a bomb calorimeter (Parr 6200 bomb calorimeter, Parr Instruments Co., Moline, IL). Dry matter was analyzed by method 934.01 (AOAC, 1990) and nitrogen determined by the method 990.03 (AOAC, 1995). The titanium dioxide (TiO$_2$) in feed and excreta was measured utilizing the method described in the study by Myers et al. (2004). AMEn values of the treatment diets were evaluated while measuring amino acid digestibility as described below in the methods. The AMEn was calculated as follows: AMEn kcal/kg= $(GE_{diet} - GE_{excreata} \times (TiO_{2\ diet}/TiO_{2\ excreta}) - 8.22 \times (N_{diet} - N_{excreta} \times TiO_{2\ diet}/TiO_{2\ excreta})$. The SID AA calculations are discussed further below in the methods.

Broilers were also measured for protein turnover in *pectoralis major* in response to dietary ME levels in
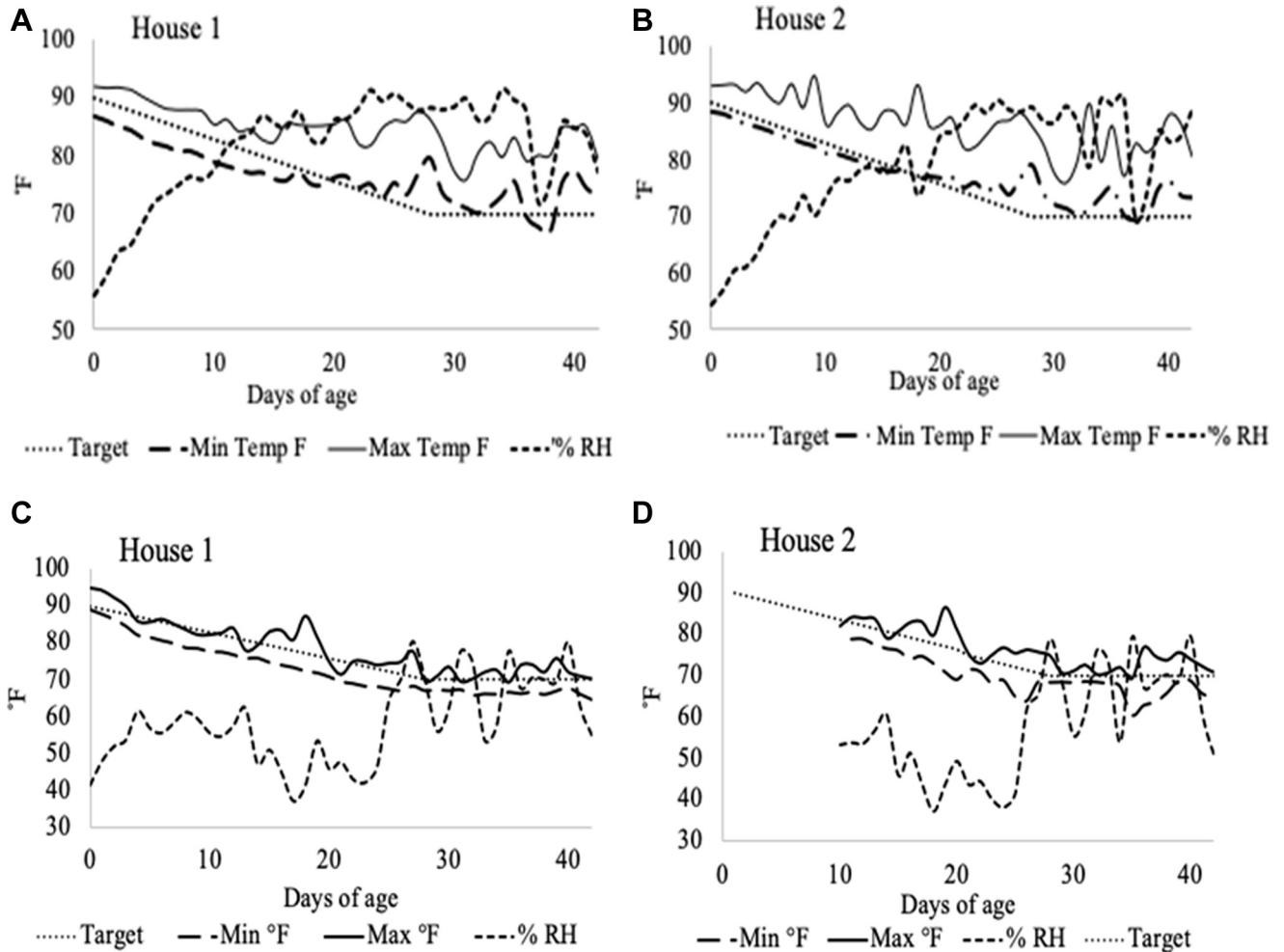
**Figure 1.** Average temperature log for 2 grow-out houses in hot season (A, B) and in cool season (C, D). Mean daily average temperature values (21–42 d) recorded for house 1 and house 2 for hot season were 77.55°F and 78.07 °F, and for cool season were 69.65 °F and 70.17 °F, respectively. Relative humidity percentage recorded for house 1 and house 2 for hot season were 86.07 and 86.01; and for cool season were 63.98 and 62.55, respectively.

hot season and cool season were measured and are discussed in detail in another article (Maharjan et al., 2020b).

### Performance Parameters and Yield Evaluation

For obtaining performance data, broilers and feed consumed were weighed at 0, 10, 21, and 42 d to determine BW, ADG, and mortality corrected FCR. Ten broilers per pen (n = 90 broilers/treatment; 900 broilers/season) were selected within one standard deviation of the average BW for each treatment for processing yield determination at 45 d and 42 d in hot season and cool season, respectively. Processing was performed after ∼8 h of feed withdrawal. Initial live weight (**LW**) and ready-to-cook parts—whole breast (boneless and skinless), tenders (boneless and skinless), wing, and thigh—were measured in terms of % LW after carcass chill (∼2 h). Abdominal fat pads were also evaluated.

### Body Composition

Body composition was determined by utilizing dual-energy X-ray absorptiometry (GE, Madison, WI) equipped with Lunar Prodigy small animal software (version 12.2). Broilers were euthanized with $CO_2$ gas and were scanned (feathers-on). Scanned broilers were used in previously determined equations (Caldas et al., 2018) to calculate the total lean, protein, fat mass, and energy content of scanned broilers. Two broilers per pen were selected at 42 d of age for scanning (18 broilers per treatment–180 broilers/season; 360 broilers in total). Broilers were selected to be within 1 SD of the average BW for the treatment.

### Standardized Ileal Digestible Amino Acids

At 42 d, 6 broilers from line A and line B were selected from each dietary treatment to be within 1 SD of the mean BW for that treatment to determine the AA digestibility of the finisher diets. Broilers were acclimated to the digestibility cages for 2 d. The five experimental

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**Table 1.** Ingredient and nutrient composition of experimental finisher diets—Hot season.

| Treatment | Finisher 1 % | Finisher 2 % | Finisher 3 % | Finisher 4 % | Finisher 5 % |
|---|---|---|---|---|---|
| Corn | 35.91 | 39.29 | 43.96 | 48.74 | 53.75 |
| Soybean meal, 48% | 20.65 | 20.08 | 20.78 | 25.29 | 29.37 |
| Wheat middlings | 20.00 | 20.00 | 16.12 | 11.42 | 5.99 |
| Sunflower meal (1st) | 9.01 | 9.01 | 9.01 | 4.06 | 0.00 |
| Sunflower meal (2nd) | 0.98 | 0.98 | 0.98 | 0.44 | 0.00 |
| Dicalcium phosphate 19 | 1.66 | 1.65 | 1.68 | 1.75 | 1.82 |
| Soybean oil | 4.42 | 4.68 | 4.99 | 5.95 | 6.81 |
| Limestone (CaCO3) | 0.73 | 0.74 | 0.73 | 0.73 | 0.72 |
| L-lysine-HCl | 0.24 | 0.25 | 0.24 | 0.17 | 0.10 |
| Sodium bicarbonate | 0.39 | 0.40 | 0.39 | 0.34 | 0.29 |
| MetAmino | 0.25 | 0.25 | 0.24 | 0.25 | 0.25 |
| Salt | 0.21 | 0.20 | 0.21 | 0.24 | 0.27 |
| Choline chloride 60% | 0.07 | 0.06 | 0.06 | 0.08 | 0.09 |
| ThreAmino | 0.07 | 0.07 | 0.07 | 0.05 | 0.03 |
| ValAmino | 0.02 | 0.02 | 0.02 | 0.01 | 0.00 |
| L-isoleucine | 0.03 | 0.03 | 0.02 | 0.00 | 0.00 |
| Vitamin premix[1] | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| Trace min premix[2] | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| Ethoxyquin[3] | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| mycoCurb[4] | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| Ameri-Bond 2x[5] | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| Filler solkafloc | 4.57 | 1.50 | 0.00 | 0.00 | 0.00 |
| Total | 99.98 | 99.98 | 100.27 | 100.29 | 100.26 |

| | Calculated | Anal[6] | Calculated | Anal[6] | Calculated | Anal[6] | Calculated | Anal[6] | Calculated | Anal[6] |
|---|---|---|---|---|---|---|---|---|---|---|
| Dry matter, % | 90.01 | 89.26 | 89.66 | 89.32 | 89.44 | 88.88 | 89.28 | 88.41 | 89.14 | 88.27 |
| Crude protein, % | 19.50 | 18.53 | 19.50 | 19.12 | 19.50 | 18.78 | 19.50 | 18.98 | 19.50 | 19.15 |
| Crude fiber, % | 5.27 | 5.38 | 5.32 | 5.34 | 5.12 | 5.08 | 3.71 | 4.21 | 2.47 | 2.47 |
| Ether extract, % | 8.28 | | 8.65 | | 9.01 | | 9.38 | | 9.75 | |
| Ash, % | 11.60 | | 8.56 | | 6.72 | | 6.57 | | 6.42 | |
| Starch, % | 27.47 | | 29.64 | | 31.84 | | 33.96 | | 36.08 | |
| Choline | 1.50 | | 1.50 | | 1.50 | | 1.50 | | 1.50 | |
| AMEn, kcal/kg | 2,800 | 2,819 | 2,925 | 3,000 | 3,050 | 3,137 | 3,175 | 3,358 | 3,300 | 3,452 |
| Ca, % | 0.85 | | 0.85 | | 0.85 | | 0.85 | | 0.85 | |
| P, % | 0.75 | | 0.75 | | 0.74 | | 0.71 | | 0.68 | |
| avP, % | 0.42 | | 0.42 | | 0.42 | | 0.42 | | 0.42 | |
| Na, % | 0.20 | | 0.20 | | 0.20 | | 0.20 | | 0.20 | |
| Cl, % | 0.23 | | 0.23 | | 0.23 | | 0.23 | | 0.23 | |
| K, % | 0.88 | | 0.88 | | 0.86 | | 0.83 | | 0.79 | |
| Electrolyte balance | 247.00 | | 247.00 | | 244.00 | | 234.00 | | 224.00 | |
| Lys, % | 1.11 | 1.08 | 1.11 | 1.10 | 1.10 | 1.07 | 1.10 | 1.10 | 1.10 | 1.10 |
| Met, % | 0.54 | 0.52 | 0.54 | 0.53 | 0.54 | 0.53 | 0.54 | 0.50 | 0.54 | 0.53 |
| M + C, % | 0.85 | 0.82 | 0.85 | 0.84 | 0.85 | 0.83 | 0.84 | 0.80 | 0.84 | 0.82 |
| Thr, % | 0.77 | 0.74 | 0.77 | 0.74 | 0.77 | 0.74 | 0.77 | 0.75 | 0.76 | 0.74 |
| Trp, % | 0.25 | | 0.24 | | 0.24 | | 0.24 | | 0.24 | |
| Arg, % | 1.35 | 1.30 | 1.34 | 1.33 | 1.34 | 1.28 | 1.32 | 1.29 | 1.31 | 1.28 |
| Lue, % | | 2.13 | | 2.05 | | 2.03 | | 2.16 | | 2.17 |
| Ile, % | 0.80 | 0.78 | 0.80 | 0.79 | 0.79 | 0.77 | 0.79 | 1.55 | 0.81 | 0.80 |
| Val, % | 0.92 | 0.91 | 0.92 | 0.92 | 0.92 | 0.90 | 0.91 | 0.92 | 0.91 | 0.90 |
| SID Lys, % | 1.00 | 1.19 | 1.00 | 1.14 | 1.00 | 1.09 | 1.00 | 1.09 | 1.00 | 1.10 |
| SID Met, % | 0.51 | 0.49 | 0.51 | 0.58 | 0.51 | 0.49 | 0.51 | 0.45 | 0.51 | 0.43 |
| SID Thr, % | 0.65 | 0.79 | 0.65 | 0.75 | 0.65 | 0.74 | 0.65 | 0.72 | 0.65 | 0.75 |
| SID Trp, % | 0.21 | 0.23 | 0.21 | 0.20 | 0.21 | 0.19 | 0.21 | 0.20 | 0.21 | 0.19 |
| SID Arg, % | 1.22 | 1.35 | 1.22 | 1.30 | 1.22 | 1.23 | 1.21 | 1.23 | 1.21 | 1.26 |
| SID Lue, % | | 1.41 | | 1.36 | | 1.34 | | 1.41 | | 1.43 |
| SID Ile, % | 0.71 | 0.84 | 0.71 | 0.79 | 0.71 | 0.77 | 0.71 | 0.78 | 0.73 | 0.81 |
| SID Val, % | 0.80 | 0.98 | 0.80 | 0.92 | 0.80 | 0.90 | 0.80 | 0.91 | 0.80 | 0.94 |

[1]Vitamin premix: Vit A, 13,227 IU/kg; Vit D3, 3,968 IU/kg; Vit E, 66 IU/kg; Vit B12, .040 mg/kg; biotin, .254 mg/kg; menadione, 3.968 mg/kg; thiamine, 3.968 mg/kg; riboflavin, 13.228 mg/kg; Vit B6, 7.937 mg/kg; niacin, 110.229 mg/kg; folic acid, 2.205 mg/kg.

[2]Trace mineral premix: Mn, 60 mg/kg (manganese sulfate); Zn, 60 mg/kg (zinc sulfate); Fe, 40 mg/kg (ferrous sulfate); Cu, 5 mg/kg (copper sulfate); I, 1.25 mg/kg (calcium iodide); Co, 0.5 mg/kg (cobalt sulfate).

[3]Santoquin: Novus International, St. Charles, MO.

[4]mycoCurb: Kemin Industries, Inc., Des Moines, IA.

[5]Ameri-Bond 2X: Borregaard LignoTech, PO Box 162, 1701 Sarpsborg, Norway.

[6]Analysis on as is basis.

finisher diets with 0.2% TiO$_2$ added were fed *ad libitum.* Feed was removed at 2,400 h for 8-h period on the evening of day 44. The broilers were fed ad libitum from 0,800 to 1,000 h (2 h period) on day 45 and were euthanized by CO$_2$ inhalation. The digesta was removed from the terminal ileum and immediately frozen in liquid

**Table 2.** Ingredient and nutrient composition of experimental finisher diets—Cool season.

| Treatment: | Finisher 1 | | Finisher 2 | | Finisher 3 | | Finisher 4 | | Finisher 5 | |
|---|---|---|---|---|---|---|---|---|---|---|
| Ingredient | % | | % | | % | | % | | % | |
| Corn | 37.79 | | 41.52 | | 51.51 | | 58.23 | | 61.09 | |
| Wheat middlings | 20.00 | | 20.00 | | 7.44 | | | | | |
| Sunflower meal, 27% CP | 10.00 | | 10.00 | | 10.00 | | 4.73 | | | |
| Soybean meal, 48% CP | 19.51 | | 18.80 | | 21.86 | | 26.98 | | 24.00 | |
| Corn gluten meal, 60% CP | | | | | | | | | 3.93 | |
| Dicalcium phosphate 19 | 1.63 | | 1.62 | | 1.71 | | 1.80 | | 1.82 | |
| Soybean oil | 4.53 | | 4.77 | | 5.11 | | 6.05 | | 6.72 | |
| Limestone | 0.76 | | 0.77 | | 0.72 | | 0.71 | | 0.78 | |
| Sodium bicarbonate | 0.39 | | 0.39 | | 0.35 | | 0.28 | | 0.32 | |
| Salt NaCl | 0.21 | | 0.20 | | 0.23 | | 0.28 | | 0.25 | |
| L-lys-HCl | 0.22 | | 0.23 | | 0.17 | | 0.09 | | 0.19 | |
| MetAmino® | 0.22 | | 0.21 | | 0.20 | | 0.21 | | 0.19 | |
| Choline Chloride 60% | 0.10 | | 0.10 | | 0.10 | | 0.11 | | 0.15 | |
| ThreAmino® | 0.09 | | 0.09 | | 0.06 | | 0.04 | | 0.06 | |
| ValAmino | 0.02 | | 0.02 | | | | | | | |
| L-isoleucine | 0.04 | | 0.05 | | 0.02 | | | | 0.01 | |
| L-arginine | | | | | | | | | | |
| Vitamin premix[1] | 0.10 | | 0.10 | | 0.10 | | 0.10 | | 0.10 | |
| Trace mineral premix[2] | 0.10 | | 0.10 | | 0.10 | | 0.10 | | 0.10 | |
| Selenium premix 60% | 0.02 | | 0.02 | | 0.02 | | 0.02 | | 0.02 | |
| Ethoxyquin[3] | 0.02 | | 0.02 | | 0.02 | | 0.02 | | 0.02 | |
| moldCurb[4] | 0.05 | | 0.05 | | 0.05 | | 0.05 | | 0.05 | |
| Filler (sand/solka-floc) | 4.2 | | 0.94 | | 0.23 | | 0.20 | | 0.20 | |
| Total | 100.00 | | 100.00 | | 100.00 | | 100.00 | | 100.00 | |

| Nutrient Composition | Calculated | Anal[5] | Calculated | Anal[5] | Calculated | Anal[5] | Calculated | Anal[5] | Calculated | Anal[5] |
|---|---|---|---|---|---|---|---|---|---|---|
| Dry matter, % | 90.49 | 89.4 | 90.17 | 89.12 | 89.92 | 88.9 | 89.66 | 88.4 | 89.69 | 88.3 |
| Crude protein, % | 19.50 | 19.6 | 19.5 | 19.52 | 19.50 | 18.9 | 19.50 | 18.8 | 19.50 | 18.5 |
| Crude fiber, % | 4.99 | | 5.04 | | 4.49 | | 3.08 | | 2.04 | |
| Ether extract, % | 8.28 | | 8.65 | | 9.01 | | 9.38 | | 9.75 | |
| Ash, % | 10.55 | | 7.31 | | 6.44 | | 6.29 | | 6.02 | |
| Starch, % | 31.73 | | 34.13 | | 37.05 | | 39.48 | | 41.70 | |
| AMEn, kcal/kg | 2,800 | 2,905 | 2,925 | 3,110 | 3,050 | 3,141 | 3,175 | 3,152 | 3,300 | 3,303 |
| Gross ME, kcal/kg | | 3,912 | | 4,127 | | 4,130 | | 4,133 | | 4,163 |
| Ca, % | 0.85 | | 0.85 | | 0.85 | | 0.85 | | 0.85 | |
| P, % | 0.77 | | 0.77 | | 0.72 | | 0.68 | | 0.66 | |
| avP, % | 0.42 | | 0.42 | | 0.42 | | 0.42 | | 0.42 | |
| Na, % | 0.20 | | 0.20 | | 0.20 | | 0.20 | | 0.20 | |
| Cl, % | 0.23 | | 0.23 | | 0.23 | | 0.23 | | 0.23 | |
| K, % | 0.86 | | 0.86 | | 0.81 | | 0.77 | | 0.65 | |
| Electrolyte balance | 243 | | 243 | | 231 | | 219 | | 189 | |
| Lys, % | 1.11 | 1.12 | 1.11 | 1.072 | 1.10 | 1.08 | 1.10 | 1.07 | 1.10 | 1.05 |
| Met, % | 0.52 | 0.51 | 0.52 | 0.494 | 0.52 | 0.50 | 0.52 | 0.50 | 0.52 | 0.48 |
| M + C, % | 0.85 | 0.84 | 0.85 | 0.816 | 0.84 | 0.80 | 0.84 | 0.80 | 0.84 | 0.79 |
| Thr, % | 0.77 | 0.80 | 0.77 | 0.773 | 0.76 | 0.77 | 0.76 | 0.77 | 0.76 | 0.76 |
| Trp, % | 0.24 | 0.24 | 0.24 | 0.245 | 0.23 | 0.24 | 0.23 | 0.24 | 0.21 | 0.22 |
| Arg, % | 1.33 | 1.36 | 1.32 | 1.297 | 1.34 | 1.32 | 1.34 | 1.30 | 1.21 | 1.15 |
| Leu, % | | 1.83 | | 1.80 | | 1.87 | | 2.09 | | 2.40 |
| Ile, % | 0.79 | 0.82 | 0.79 | 0.816 | 0.79 | 0.81 | 0.79 | 0.82 | 0.79 | 0.79 |
| Val, % | 0.92 | 0.95 | 0.92 | 9.28 | 0.91 | 0.92 | 0.92 | 0.91 | 0.90 | 0.88 |
| SID Lys, % | 1.00 | 1.04 | 1.00 | 0.92 | 1.00 | 0.94 | 1.00 | 0.94 | 1.00 | 1 |
| SID Met, % | 0.50 | 0.54 | 0.49 | 0.57 | 0.49 | 0.54 | 0.49 | 0.54 | 0.49 | 0.50 |
| SID Thr, % | 0.65 | 0.63 | 0.65 | 0.61 | 0.65 | 0.60 | 0.65 | 0.59 | 0.65 | 0.61 |
| SID Trp, % | 0.21 | 0.23 | 0.20 | 0.21 | 0.20 | 0.24 | 0.20 | 0.23 | 0.18 | 0.25 |
| SID Arg, % | 1.21 | 1.14 | 1.20 | 1.02 | 1.24 | 1.11 | 1.25 | 1.10 | 1.12 | 1.06 |
| SID Leu, % | | 1.06 | | 0.91 | | 1.07 | | 1.03 | | 1.37 |
| SID Ile, % | 0.71 | 0.78 | 0.71 | 0.68 | 0.71 | 0.75 | 0.72 | 0.71 | 0.71 | 0.78 |
| SID Val, % | 0.80 | 0.79 | 0.80 | 0.72 | 0.80 | 0.73 | 0.82 | 0.68 | 0.80 | 0.74 |

[1]Vitamin premix: Vit A, 13,227 IU/kg; Vit D3, 3,968 IU/kg; Vit E, 66 IU/kg; Vit B12, .040 mg/kg; biotin, .254 mg/kg; menadione, 3.968 mg/kg; thiamine, 3.968 mg/kg; riboflavin, 13.228 mg/kg; Vit B6, 7.937 mg/kg; niacin, 110.229 mg/kg; folic acid, 2.205 mg/kg.

[2]Trace mineral premix: Mn, 60 mg/kg (manganese sulfate); Zn, 60 mg/kg (zinc sulfate); Fe, 40 mg/kg (ferrous sulfate); Cu, 5 mg/kg (copper sulfate); I, 1.25 mg/kg (calcium iodide); Co, 0.5 mg/kg (cobalt sulfate).

[3]Santoquin: Novus International, St. Charles, MO.

[4]mycoCurb: Kemin Industries, Inc., Des Moines, IA.

[5]Analysis on as is basis.

nitrogen. The digesta from each broiler was then freeze-dried and analyzed for AA content by reverse-phase HPLC utilizing AOAC 982.30 and AOAC 985.28 methods (AOAC, 1990) as discussed by Caldas et al. (2018). The experimental diets with 0.2% TiO$_2$ were also analyzed for AA content. The titanium in feed and digesta was measured using the method described in the study by Myers et al. (2004). The apparent AA

**Table 3.** Dietary energy levels and amino acid levels in the study design.[1]

| Treatment | Line | AMEn (kcal/kg) | dlys | dM + C:dLys | dThr: dLys | dVal: dLys | dIle: dLys | dTry: dLys | dArg: dLys |
|---|---|---|---|---|---|---|---|---|---|
| 1 | A/B | 2,800 | 1.00* | 76 | 65 | 80 | 71 | 16 | 105 |
| 2 | | 2,925 | | | | | | | |
| 3 | | 3,050 | | | | | | | |
| 4 | | 3,175 | | | | | | | |
| 5 | | 3,300 | | | | | | | |

[1]Crude protein (CP) of the experimental diets 19.50%; Ratio of amino acid is given in percent and is kept constant across dietary ME levels.

digestibility (**AID**) was calculated using the expression (Maharjan et al., 2019)

$$AID = 1 - [(Ci / Co) \times (Xo / Xi)]$$

where, Ci is the concentration of TiO2 present in diet, Co is the concentration of TiO2 present in digesta; Xo is the AA content in digesta; and Xi is the AA content present in diet. All values for Ci, Co, Xo, and Xi were expressed on % DM basis. Digestibility coefficient values for each AA were determined.

The AID values were converted to SID values using basal endogenous AA losses (BEL) for SID calculations (Blok and Dekker, 2017), and using the following expression

$$SID\ coefficient\ (\%) = AID\ (\%) + (BEL\ of\ AA\ (g / kg\ DM) / AA\ content\ of\ diet\ (g / kg)) \times 100$$

The SID coefficients were then used to calculate the % standardized ileal digestible AA in experimental diets for each AA using the expression;

% standardized ileal digestible AA = (SID coefficient * % AA in diet ("as is")

### Data Analysis

The data obtained for variables measured were analyzed by one-way ANOVA using JMPro 14 (SAS Institute, Inc., Cary, NC). Mean values were obtained for variables measured (BW, FCR, ADG, processing yields). One-way ANOVA was performed to understand the dietary treatment effects within each line. Significant means for response variable measured between dietary treatments within each line were measured using a Student t test or HSD test where appropriate. Means were considered significant with a P value $\leq 0.05$. For understanding if there was any dietary ME level (factor A) and broiler line (factor B) interaction on the response variable, two-way ANOVA model was utilized as follows:

$$Yijk = \mu + Ti + Bj + (TB)ij + eijk$$

where,
$\mu$ = mean,
Ti = effect of $i^{th}$ level of factor A,
Bj = effect of $j^{th}$ level of factor B,
(TB)ij = effect of interaction between the $i^{th}$ level of factor

A and the $j^{th}$ level of factor B,
eijk = random error associated with the $k^{th}$ replicate.

General linear regression analyses were applied for FCR, body composition, and yield data to determine the relationship of dietary ME levels on these response variables. The following equation was utilized: y = mx + c, where y = response variable x = ME levels, m = slope, and c = intercept.

## RESULTS

### Feed and Nutrient Intakes

There was no line × diet interaction effect on cumulative 22–42 d FI, protein intake, or energy intake. Feed intake and protein intake decreased linearly as the dietary ME levels increased for both hot season and cool season (Table 4; Figure 2).

Hot season: There was a linear decrease in FI of 75 g and 77 g for line A ($R^2 = 0.93$) and line B ($R^2 = 0.95$) for every 10% increase in dietary ME for treatment diets (Figure 2). Cumulative FI for line B broilers was higher for 22–42 d than for the line A broilers (Table 4). This resulted in the line B broilers consuming higher protein and higher energy than the line A broilers from 22 to 42 d. Cumulative 22–42 d FI per bird was 3,510 g and 3,602 g for line A and line B broilers, respectively. Cumulative 22–42 d protein intake per bird was 649 g and 666 g for line A and line B broilers, respectively. Cumulative 22–42 d energy intake per bird was 10,693 kcal and 11,679 kcal for line A and line B broilers, respectively.

Cool season: There was a linear decrease in FI of 35 g and 58 g for line A ($R^2 = 0.80$) and line B ($R^2 = 0.91$) for every 10% increase in ME for treatment diets evaluated (Figure 2). Cumulative feed and nutrient intakes were not different between the 2 lines at any time during all feeding phases including day 22–42 (Table 4). For the 22–42 d period, the cumulative FI per bird was 3,745 and 3,712 kg for line A and line B broilers, respectively ($P = 0.2706$). For this period the line A and line B broilers consumed 714 g and 708 g of protein, respectively ($P = 0.2804$). The AMEn intake was 11,372 and 11,269 kcal per bird for line A and line B birds, respectively ($P = 0.2609$).

**Table 4.** Feed intake (FI) and nutrient intake per bird of 2 broiler lines fed 5 dietary ME levels (kcal/kg) in hot season and cool season.[1]

| | Hot season | | | | | | Cool season | | | | | |
| | 0–21 d | | | 22–42 d | | | 0–21 d | | | 22–42 d | | |
| | Cumulative FI | Protein intake | Energy intake | Feed intake | Protein intake | Energy intake (ME) | Feed | Protein | ME | Feed | Protein | ME |
| Line/ME level | g | g | kcal/b | g | g | kcal/b | g/b | g/b | kcal/b | g/b | g/b | kcal/b |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Line A | 1,200[b] | 248.5[b] | 3,704.03[b] | 3,510[b] | 649[b] | 10,693[b] | 1,225 | 260 | 3,759 | 3,745 | 714 | 11,372 |
| Line B | 1,260[a] | 260.8[a] | 3,878.24[a] | 3,602[a] | 666[a] | 11,679[a] | 1,218 | 258 | 3,737 | 3,712 | 708 | 11,269 |
| SEM | 5 | 12.21 | 17.03 | 80 | 10 | 114 | 4.79 | 1.01 | 14.72 | 20.9 | 4.02 | 85 |
| P-value | 0.0004 | 0.0005 | 0.0051 | <0.0001 | <0.0001 | <0.0001 | 0.2925 | 0.2517 | 0.3020 | 0.2706 | 0.2804 | 0.2609 |
| A, 2,800 | | | | 3,660[a] | 677 | 10,248[b] | | | | 3,843[a] | 754[a] | 10,760 |
| A, 2,925 | | | | 3,620[b] | 670 | 10,589[b] | | | | 3,789[a,b] | 740[a] | 11,083 |
| A, 3,050 | | | | 3,480[c] | 644 | 10,614[a,b] | | | | 3,752[a,b] | 708[b] | 11,256 |
| A, 3,175 | | | | 3,410[c] | 631 | 10,827[a,b] | | | | 3,644[b] | 683[c] | 11,570 |
| A, 3,300 | | | | 3,390[c] | 627 | 11,187[a] | | | | 3,695[b] | 683[c] | 12,194 |
| B, 2,800 | | | | 3,790[a] | 701 | 10,612[b] | | | | 3,850[a] | 756[a] | 10,780 |
| B, 2,925 | | | | 3,640[a,b] | 673 | 10,647[b] | | | | 3,726[a,b] | 727[a] | 10,899 |
| B, 3,050 | | | | 3,590[b,c] | 664 | 10,950[a,b] | | | | 3,723[a,b] | 703[b] | 11,169 |
| B, 3,175 | | | | 3,530[c,d] | 653 | 11,208[a,b] | | | | 3,675[b] | 689[b,c] | 11,668 |
| B, 3,300 | | | | 3,460[d] | 640 | 11,418[a] | | | | 3,584[c] | 662[c] | 11,827 |
| SEM | | | | 80 | 20 | 255 | | | | 46.58 | 8.96 | 190 |
| P-value[2] | | | | 0.0057 | 0.0502 | 0.0064 | | | | 0.0002 | <0.0001 | 0.0625 |

[1]Different letters in superscripts represent significantly different means between dietary ME levels within line in each column.
[2]P-values presented are for combined lines for dietary ME levels. No diet by line interaction was observed.

**A**



**B**
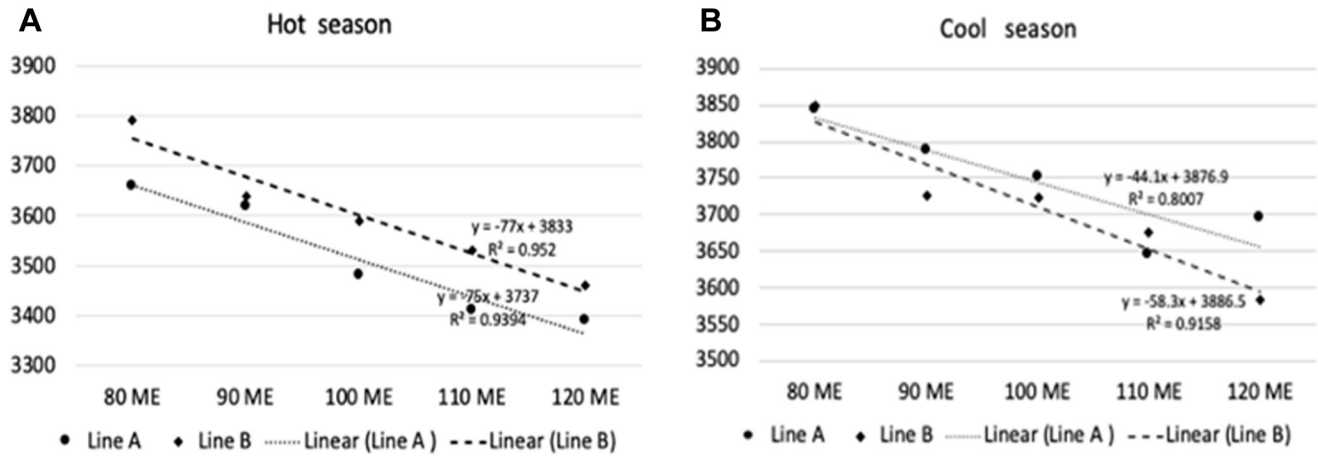


**Figure 2.** *Linear fit of lines for feed intake (g) for line A and line B for dietary ME levels in hot season (A) and cool season (B). *80 ME, 90 ME, 100 ME, 110 ME, and 120 ME is equivalent to 2,800, 2,925, 3,050, 3,175 and 3,300 kcal/kg of feed.

### Body Weight, Average Daily Gain, and Feed Conversion Ratio

There was no line $\times$ diet interaction effect on FCR at any age period. The FCR dropped linearly as the dietary ME levels increased (Table 5; Figure 3).

Hot season: Line B had higher BW throughout the trial period ($P < 0.05$) than line A. ADG increased as the dietary ME level increased. The FCR decreased linearly by 0.059 and 0.07 units for line A ($R^2 = 0.98$) and line B ($R^2 = 0.93$) across ME levels (Figure 3). The cumulative FCR was lower for line B ($P > 0.05$) for 22–42 d or 0–42 d than for line A.

Cool season: There was no difference in BW between lines at day 21 and day 35 ($P > 0.05$), whereas the higher BW for line A was observed at day 42 ($P < 0.05$). Cumulative ADG was higher for line A ($P < 0.05$), whereas ADG increased across dietary ME levels for both lines. The FCR decreased linearly by 0.08 units for both lines ($R^2 > 0.97$) across dietary ME levels (Figure 3). Similarly, line A had lower FCR values for 22–42 d and 0–42 d (Table 5).

### Body Composition

Cumulative total body mass was higher for line B in hot season ($P < 0.05$), whereas it was not different between lines in cool season ($P > 0.05$). The % lean and % protein mass were higher for line B than for line A ($P < 0.05$) for both seasons (Table 6). Total body mass increased linearly for both lines across ME levels. The cumulative % fat mass at each ME level was higher for line A ($P < 0.05$) than for line B. There was a linear decrease in % protein (hot season: 0.14% for line A and 0.19% for line B; cool season: 0.28% for line A and 0.25% for line B), whereas the % fat linearly increased (hot season: 0.53% for line A and 0.38% for line B; cool season: 0.66% for line A and 0.74% for line B) across ME levels (Figure 4). The rate of increases for % fat mass across ME levels was higher for cool season as given by higher slope values (Figure 4) for both lines.

### Processing Yield

There were differences in cumulative % weights (of LW) for wing, breast, tenders, and leg quarters for both lines and seasons ($P < 0.05$) (Table 7). However, the % weight of LW for wings, breast filet, tenders, and leg quarters were not different when compared between treatment diets in hot season ($P > 0.05$). The % breast weight and % tenders' weight of the LW between dietary ME levels (the lowest and highest ME) were different mainly in cool season ($P < 0.05$). The % fat pad of total LW increased linearly by 0.22 and 0.21% in hot season and 0.2 and 0.18% in cool season for line A and line B, respectively ($R^2 > 0.95$), for every 10% increase across dietary ME levels. The cumulative % fat pad for combined ME levels was higher for line A ($P < 0.05$) for both seasons, with overall fat pad % higher for hot season than cool season.

### Standardized Ileal Digestible Amino Acids

There was no difference between lines in standardized ileal digestibility (**SID**) coefficient values ($P > 0.05$) for combined analysis of treatment diets for hot season or cool season. The % standardized ileal digestible amino acids intake decreased ($P < 0.05$) for the most essential and nonessential amino acids for both lines with increasing dietary ME level in hot season whereas this trend was not observed for cool season (Table 8). Leucine was the only amino acid that the SID intake increased over the increase in dietary ME levels for both lines and seasons.

### DISCUSSION

Dietary energy is the largest cost factor for poultry operation. The utilization of dietary energy by modern broiler lines needs further exploration. Finding the appropriate protein to energy ratio in the diet can be crucial for the optimal performance of broilers. The performance and processing yield benefits by increasing

**Table 5.** Body weight (BW) and FCR per bird of 2 broiler lines fed 5 dietary ME levels (kcal/kg) in hot season and cool season.[1]

| | Hot season | | | | | | | | Cool season | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | BW | | | | | ADG | FCR | | BW | | | | | ADG | FCR | |
| BW | Day 0 | Day 10 | Day 21 | Day 35 | Day 42 | 22–42 d | 22–42 d | 0–42 d | Day 0 | Day 10 | Day 21 | Day 35 | Day 42 | 22–42 d | 21–42 d | 0–42 d |
| LINE/ME level | g | g | g | g | g | g | g:g | g:g | g | g | g | g | g | g | g:g | g:g |
| Line A | $38.63^b$ | $270^b$ | $950^b$ | $2,240^b$ | $2,810^b$ | $88^b$ | 2.09 | 1.83 | $43^b$ | 302 | 988 | 2,350 | $3,029^a$ | $96^a$ | $1.94^b$ | $1.74^b$ |
| Line B | $41.04^a$ | $280^a$ | $1010^a$ | $2,350^a$ | $2,930^a$ | $91^a$ | 2.07 | 1.81 | $46^a$ | 302 | 986 | 2,303 | $2,922^b$ | $94^b$ | $2.01^a$ | $1.76^a$ |
| SEM | 0.0922 | 1.5 | 4.4 | 10.9 | 15.7 | 0.7 | 0.0215 | 0.0132 | 0.1 | 3.1 | 10.2 | 22.5 | 0.0283 | 0.6 | 0.0109 | 0.0058 |
| P-value | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0022 | 0.9785 | 0.2479 | <0.0001 | 0.8644 | 0.9158 | 0.2686 | 0.0479 | 0.0233 | <0.0001 | 0.0010 |
| A,2,800 | 38.83 | 270 | 950 | $2,210^b$ | $2,760^b$ | $86^b$ | $2.21^a$ | $1.92^a$ | 44 | 306 | 984 | $2,306^b$ | $2,950^b$ | $94^b$ | $2.10^a$ | $1.84^a$ |
| A,2,925 | 38.56 | 270 | 950 | $2,220^b$ | $2,810^{a,b}$ | $89^{a,b}$ | $2.13^{a,b}$ | $1.87^{a,b}$ | 43 | 304 | 985 | $2,313^b$ | $2,962^b$ | $93^b$ | $2.05^a$ | $1.80^a$ |
| A,3,050 | 38.76 | 260 | 930 | $2,210^b$ | $2,780^{a,b}$ | $88^{a,b}$ | $2.1^{a,b}$ | $1.84^b$ | 43 | 300 | 990 | $2,376^a$ | $3,042^{a,b}$ | $97^a$ | $1.93^b$ | $1.73^b$ |
| A,3,175 | 38.37 | 270 | 960 | $2,230^b$ | $2,800^{a,b}$ | $87^{a,b}$ | $1.04^{b,c}$ | $1.8^{b,c}$ | 43 | 302 | 997 | $2,389^a$ | $3,089^a$ | $98^a$ | $1.84^c$ | $1.67^c$ |
| A,3,300 | 38.64 | 270 | 970 | $2,310^a$ | $2,900^a$ | $92^a$ | $1.96^c$ | $1.76^c$ | 43 | 301 | 986 | $2,365^a$ | $3,101^a$ | $98^a$ | $1.80^c$ | $1.64^c$ |
| B,2,800 | 41.24 | 270 | 1,000 | $2,300^b$ | $2,860^b$ | $88^b$ | $2.18^a$ | $1.88^a$ | 46 | 301 | 972 | $2,244^b$ | $2,862^b$ | $91^b$ | $2.18^a$ | $1.87^a$ |
| B,2,925 | 41.01 | 270 | 990 | $2,310^b$ | $2,870^{a,b}$ | $89^{a,b}$ | $2.17^{a,b}$ | $1.86^a$ | 46 | 306 | 993 | $2,307^a$ | $2,850^b$ | $94^{a,b}$ | $2.10^{a,b}$ | $1.82^{a,b}$ |
| B,3,050 | 40.99 | 280 | 1,030 | $2,380^a$ | $2,970^{a,b}$ | $93^{a,b}$ | $2.06^{a,b}$ | $1.8^{a,b}$ | 46 | 297 | 986 | $2,306^a$ | $2,926^{a,b}$ | $93^{a,b}$ | $2.00^{b,c}$ | $1.76^b$ |
| B,3,175 | 40.92 | 280 | 1,020 | $2,390^a$ | $2,960^{a,b}$ | $93^{a,b}$ | $2.03^{b,c}$ | $1.78^{b,c}$ | 45 | 304 | 990 | $2,331^a$ | $3,001^a$ | $97^a$ | $1.90^{c,d}$ | $1.69^c$ |
| B,3,300 | 41.05 | 280 | 1,010 | $2,390^a$ | $2,990^a$ | $94^a$ | $1.9^c$ | $1.71^c$ | 45 | 299 | 990 | $2,326^a$ | $2,970^{a,b}$ | $95^{a,b}$ | $1.87^d$ | $1.68^c$ |
| SEM | 0.2027 | 3.3 | 9.7 | 23.9 | 34.4 | 1.5 | 0.0419 | 0.023 | 0.2 | 4.2 | 13.9 | 30.8 | 38.7 | 1.2 | 0.0239 | 0.0129 |
| P-value[2] | 0.4256 | 0.1275 | 0.2041 | 0.0014 | 0.0027 | 0.0035 | <0.0001 | <0.0001 | 0.1666 | 0.1940 | 0.7037 | 0.0076 | <0.0001 | 0.0002 | <0.0001 | <0.0001 |

[1]Different letters in superscripts represent significantly different means between dietary ME levels within line in each column.
[2]P-values presented are for combined lines for dietary ME levels. No diet by line interaction was observed.
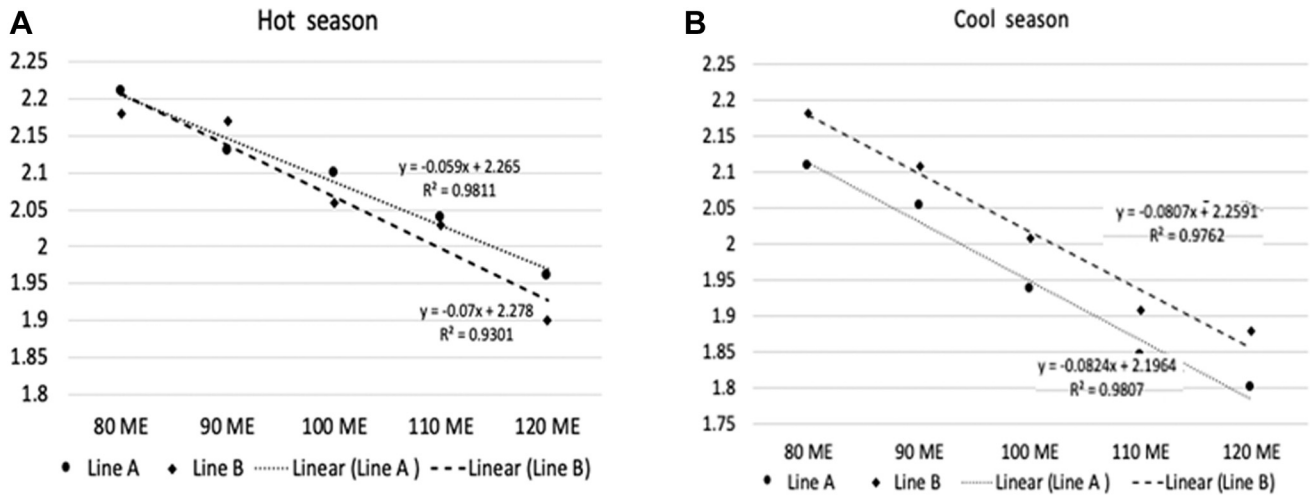
**Figure 3.** *Linear fit of lines for FCR (22–42 d) for Line A and Line B for dietary ME levels (kcal/kg) in hot season (A) and cool season (B). *80 ME, 90 ME, 100 ME, 110 ME, and 120 ME is equivalent to 2,800, 2,925, 3,050, 3,175 and 3,300 kcal/kg of feed.

dietary amino acid density is becoming more evident (Temim et al., 1999; Viera and Angel, 2012; Maharjan et al., 2020c), whereas less is known regarding dietary energy density. The present study evaluated the effects of dietary ME levels ranged from 2,800 to 3,300 kcal/kg on performance parameters and processing yield characteristics.

Decreasing dietary ME levels resulted in a FI increment of 61.25 g/b for every 10% increase in energy level in 22–42 d for combined lines and seasons in this study. Even though there was a decreased FI during 22–42 d with higher ME diets (>100% ME levels), there were still increased energy intake per bird. The FCR values dropped linearly as the dietary ME levels increased for both lines and seasons (Table 5; Figure 3). Reduced FCR for broilers fed higher ME diets as reported in this study were also observed in other studies conducted with meat broilers fed high energy diets (3,250 kcal ME/kg vs. 3,050 kcal ME/kg) reared at grow-out
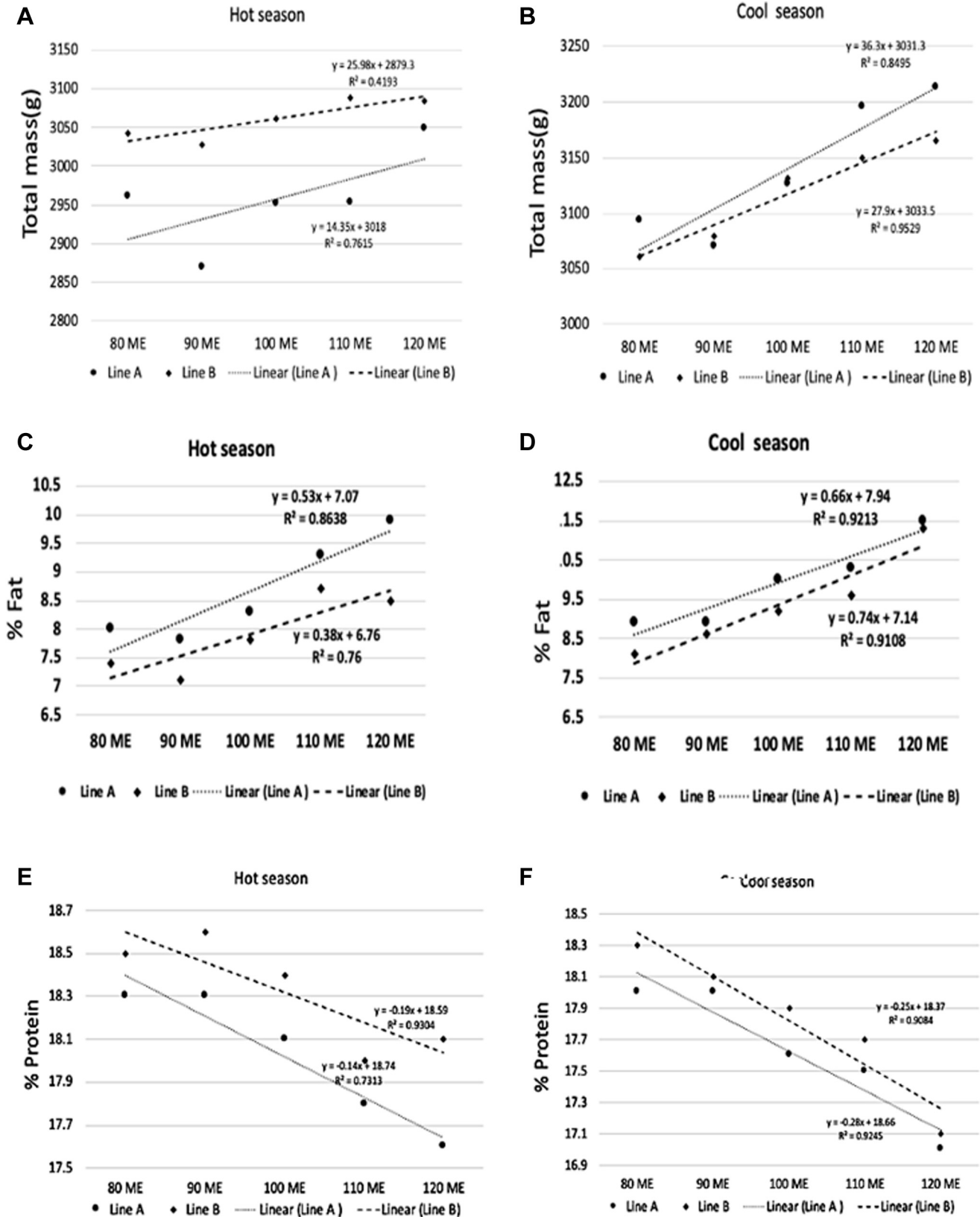
temperatures from 21.1 C to 35 C (Cheng et al., 1997; Gopinger et al., 2017; Liu et al., 2019). The increased FI of broilers fed lower ME diets (<100% ME levels) resulted in higher protein intake, which resulted in an increase in % whole body protein (Table 6). Broilers fed high energy density diets did not produce different processing characteristics (% breast, tenders, wings or leg quarters of LW) in present study (at least for hot season) as compared with low energy density diets except for % fat pad of LW (Table 7). Similar results for yield were reported in other studies that tested various dietary energy levels (Gopinger et al., 2017; Liu et al., 2019; Maynard et al., 2019), which was attained by actually increasing the FI as observed in present study. The decreased FI of broilers with higher ME diets (>100% ME levels) and thus decreased protein intake, compared with lower ME diets potentially indicated improved use of available dietary protein with higher ME level diets. High energy diets could optimize the dietary amino acid utilization

**Table 6.** Body composition in percentage of total body mass at 42 d of 2 lines of broilers reared from 22–42 d of age on 5 different dietary ME levels (kcal/kg).[1]

| | | Hot season | | | | | Cool season | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Line/ME level | Total mass (g) | Lean % | Protein % | Fat % | Energy kcal/g | Total mass (g | Lean % | Protein % | Fat % | Energy kcal/g |
| Line A | 2,957.24 | 88.4[b] | 18[b] | 8.6[a] | 1.8[a] | 3,140.2 | 86.1 | 17.6 | 9.9 | 1.86 |
| Line B | 3,061.06 | 89.7[a] | 18.4[a] | 7.9[b] | 1.77[b] | 3,117.2 | 87.1 | 17.8 | 9.4 | 1.84 |
| P-value | <0.0001 | 0.0002 | <0.0001 | 0.0003 | 0.0011 | 0.1760 | 0.0046 | 0.0068 | 0.0047 | 0.0037 |
| A, 2,800 | 2,961[a,b] | 89.6[a] | 18.3[a] | 8[b] | 1.8[b] | 3,094[b] | 87.9[a] | 18[a] | 8.9[c] | 1.81[c] |
| A, 2,925 | 2,871[b] | 89.9[a] | 18.3[a] | 7.8[b] | 1.8[b] | 3,071[b] | 87.9[a] | 18[a] | 8.9[c] | 1.82[c] |
| A, 3,050 | 2,952[a,b] | 88.9[a] | 18.1[a] | 8.3[b] | 1.8[b] | 3,127[a,b] | 86.1[a,b] | 17.6[b] | 10[b] | 1.86[b] |
| A, 3,175 | 2,954[a,b] | 87.3[b] | 17.8[b] | 9.3[a] | 1.8[b] | 3,196[a] | 85.4[b] | 17.5[b] | 10.3[b] | 1.88[b] |
| A, 3,300 | 3,050[a] | 86.1[b] | 17.6[b] | 9.9[a] | 1.9[a] | 3,213[a] | 83.2[c] | 17[c] | 11.5[a] | 1.94[a] |
| B, 2,800 | 3,043[a,b] | 90.5[a] | 18.5[a] | 7.4[b] | 1.7[b] | 3,061[b] | 89.4[a] | 18.3[a] | 8.1[d] | 1.78[d] |
| B, 2,925 | 3,028[b] | 91[a] | 18.6[a] | 7.1[b] | 1.7[b] | 3,079[b] | 88.5[a,b] | 18.1[a,b] | 8.6[c,d] | 1.80[c,d] |
| B, 3,050 | 3,062[a,b] | 90[a] | 18.4[a] | 7.8[b] | 1.8[b] | 3,131[a,b] | 87.4[b,c] | 17.9[b,c] | 9.2[b,c] | 1.83[b,c] |
| B, 3,175 | 3,088[a] | 88.3[b] | 18[b] | 8.7[a] | 1.8[a] | 3,150[a] | 86.7[c] | 17.7[c] | 9.6[b] | 1.85[b] |
| B, 3,300 | 3,084[a] | 88.7[b] | 18.1[b] | 8.5[a] | 1.8[a] | 3,165[a] | 83.7[d] | 17.1[d] | 11.3[a] | 1.93[a] |
| SEM | 34.54 | 0.5 | 0.1 | 0.3 | 0 | 26.52 | 0.57 | 0.13 | 0.32 | 0.01 |
| P-value[2] | 0.0207 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 |

[1]Different letters in superscripts represent significantly different means between dietary ME levels within line in each column.
[2]P-values presented are for combined lines for dietary ME levels. No diet by line interaction was observed.

**A** Hot season

$y = 25.98x + 2879.3$
$R^2 = 0.4193$

$y = 14.35x + 3018$
$R^2 = 0.7615$

Total mass(g)

80 ME  90 ME  100 ME  110 ME  120 ME

● Line A   ◆ Line B   ┈┈ Linear (Line A)   ─ ─ Linear (Line B)

**B** Cool season

$y = 36.3x + 3031.3$
$R^2 = 0.8495$

$y = 27.9x + 3033.5$
$R^2 = 0.9529$

Total mass(g)

80 ME  90 ME  100 ME  110 ME  120 ME

● Line A   ◆ Line B   ┈┈ Linear (Line A)   ─ ─ Linear (Line B)

**C** Hot season

$y = 0.53x + 7.07$
$R^2 = 0.8638$

$y = 0.38x + 6.76$
$R^2 = 0.76$

% Fat

80 ME  90 ME  100 ME  110 ME  120 ME

● Line A   ◆ Line B   ┈┈ Linear (Line A)   ─ ─ Linear (Line B)

**D** Cool season

$y = 0.66x + 7.94$
$R^2 = 0.9213$

$y = 0.74x + 7.14$
$R^2 = 0.9108$

% Fat

80 ME  90 ME  100 ME  110 ME  120 ME

● Line A   ◆ Line B   ┈┈ Linear (Line A)   ─ ─ Linear (Line B)

**E** Hot season

$y = -0.19x + 18.59$
$R^2 = 0.9304$

$y = -0.14x + 18.74$
$R^2 = 0.7313$

% Protein

80 ME  90 ME  100 ME  110 ME  120 ME

● Line A   ◆ Line B   ── Linear (Line A)   ─ ─ Linear (Line B)

**F** Cool season

$y = -0.25x + 18.37$
$R^2 = 0.9084$

$y = -0.28x + 18.66$
$R^2 = 0.9245$

% Protein

80 ME  90 ME  100 ME  110 ME  120 ME

● Line A   ◆ Line B   ── Linear (Line A)   ─ ─ Linear (Line B)

**Figure 4.** *Linear fit of lines for total body mass (A, B), % fat of total body mass (C, D), and % protein of total body mass (E, F) for line A and line B at 42 d for dietary ME levels (kcal/kg) in hot season and cool season. *80 ME, 90 ME, 100 ME, 110 ME, and 120 ME is equivalent to 2,800, 2,925, 3,050, 3,175, and 3,300 kcal/kg of feed.

which increases the protein accretion potential of broilers. This is also justified by higher SID intake for leucine across dietary ME for both lines and seasons as

leucine almost entirely mediate translation initiation processes in protein synthesis of skeletal muscle (Norton and Layman, 2006; Stipanuk, 2007). Jackson

**Table 7.** Ready-to-cook and fat pad yield in percentage of live weight (LW, g) of 2 broiler lines fed dietary ME levels (kcal/kg) in hot season and cool season.[1]

| Line/ME level | 45-d processing, hot season | | | | | | 42-d processing, cool season | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | LW | Fat pad | Wings | Breast filet | Tenders | Leg quarters | LW | Fat pad | Wings | Breast filet | Tenders | Leg quarters |
| Line A | 3,016[b] | 2.5[a] | 7.7[a] | 20.5[a] | 4.34[a] | 23[b] | 3,173 | 1.4[a] | 7.6[b] | 20.2[a] | 4.3[a] | 22.5 |
| Line B | 3,135[a] | 2.3[b] | 7.6[b] | 20.1[b] | 4.27[b] | 23.2[a] | 3,162 | 1.2[b] | 7.7[a] | 19.7[b] | 4.2[b] | 22.6 |
| P-value | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.0010 | 0.0201 | 0.4124 | <0.0001 | 0.0325 | 0.0019 | 0.0088 | 0.2840 |
| A, 2,800 | 2,956 | 2.1[c] | 7.8 | 20.6 | 4.4 | 23.2 | 3,088 | 1[c] | 7.6 | 20.4[a] | 4.4[a] | 22.6 |
| A, 2,925 | 3,001 | 2.2[c] | 7.6 | 20.6 | 4.4 | 23 | 3,083 | 1.1[c] | 7.7 | 20.4[a] | 4.4[a] | 22.2 |
| A, 3,050 | 3,017 | 2.5[b] | 7.7 | 20.6 | 4.3 | 22.9 | 3,187 | 1.5[b] | 7.5 | 20.3[a] | 4.3[a,b] | 22.5 |
| A, 3,175 | 3,014 | 2.8[a] | 7.7 | 20.3 | 4.3 | 23.3 | 3,216 | 1.5[b] | 7.5 | 19.5[b] | 4.2[b] | 22.7 |
| A, 3,300 | 3,089 | 2.9[a] | 7.8 | 20.7 | 4.3 | 22.8 | 3,291 | 1.8[a] | 7.4 | 20.2[a] | 4.2[b] | 22.1 |
| B, 2,800 | 3,050 | 1.9[c] | 7.6 | 20.3 | 4.3 | 23.1 | 3,082 | 0.9[d] | 7.6 | 20.1[a] | 4.3[a] | 22.5 |
| B, 2,925 | 3,077 | 2[c] | 7.7 | 20 | 4.3 | 23.2 | 3,153 | 1[d] | 7.7 | 20[a,b] | 4.2[a] | 22.5 |
| B, 3,050 | 3,160 | 2.2[b] | 7.7 | 20.1 | 4.3 | 23.2 | 3,128 | 1.2[c] | 7.6 | 19.7[a,b] | 4.3[a] | 22.7 |
| B, 3,175 | 3,169 | 2.5[a] | 7.6 | 19.9 | 4.3 | 23.3 | 3,228 | 1.4[b] | 7.6 | 19.6[b,c] | 4.3[a] | 22.7 |
| B, 3,300 | 3,217 | 2.7[a] | 7.5 | 20.3 | 4.3 | 23.1 | 3,221 | 1.6[a] | 7.6 | 19.2[c] | 4.1[b] | 22.6 |
| SEM | 19.41 | 0.08 | 0.04 | 0.16 | 0.04 | 0.12 | 20.84 | 0.01 | 0.01 | 0.05 | 0.01 | 0.04 |
| P-value[2] | <0.0001 | <0.0001 | 0.1871 | 0.1159 | 0.1053 | 0.0920 | <0.0001 | <0.0001 | 0.1262 | 0.0015 | 0.0018 | 0.3567 |

[1]Different letters in superscripts represent significantly different means between dietary ME levels within line in each column.
[2]P-values presented are for combined lines for dietary ME levels. No diet by line interaction was observed.

et al. (1982) studied the effects of alteration of nutrient densities of 6 levels of dietary protein (16–36%) and energy (2,600–3,600 kcal/kg) on performance and found significant interactions between dietary protein and energy suggesting the need for balanced protein-to-energy ratio.

All animals including avian species possess natural ability to control FI based on intent to normalize energy intake as per the body requirement. When energy intake is decreased, there is an increased intake of amino acid per Mcal that leads to decreased deposition of carcass fat or vice versa (Leeson et al., 1996). There was increased fat mass ($P < 0.05$) as dietary ME level increased in both seasons in current study. Whole-body % protein mass of total body mass measured at day 42 linearly dropped for both lines across all ME levels for both seasons ($R^2 = \sim 0.9$). Another study found a similar response in broilers with protein and fat body composition when fed lowered energy diets in the finishing phase as observed in this study (Leeson et al., 1996).

Protein deposition that occurs through protein turnover processes is energy-dependent process (Waterlow, 1984). Based on the calculated energy cost for protein synthesis, 4 mol ATP + GTP per mole of peptide bond would require a minimum of 0.86 kcal/g protein of average composition yet (Waterlow, 1984; Bergen, 2008). The protein synthesis is followed by the almost equivalent amount of breakdown which the exact stoichiometry for breakdown energy cost has not been completely worked out yet (Waterlow, 1984; Bergen, 2008); however, it is predicted that it is half the amount (0.40 kcal/g) compared with synthesis (Fan et al., 2008). The balance of protein: energy is essential for optimal protein turnover (Maharjan et al., 2020a). Optimal protein (digestible amino acids)-to-energy (calorie) ratio in diet potentiates for optimal PT gain for skeletal protein deposition, the concept discussed earlier in many other studies (Kyriazakis and Emmans, 1992; Maharjan et al., 2020b). Broilers had the highest fractional synthesis rate (**FSR**) in *pectoralis major* for finishing phase

consuming $\sim 3.48$ g digestible Lys/Mcal (Maharjan et al., 2020a) which is higher than the g dLys consumed/Mcal in present study. Increasing the g digestible Lys/Mcal $\geq 3.48$ as reported by Maharjan et al. (2020a,b) during the cool season improved the FSR by $\sim 5\%$ per day. This indicates that FSR is more responsive to increased dietary digestible amino acid than to dietary energy changes. Achieving the optimal g dLys/Mcal is important; however it is equally essential to have adequate energy level of the diet to attain optimal amino acid utilization for protein synthesis.

Processing data in the present study showed no difference in yield ($P > 0.05$) in % breast, tenders, leg quarters, and wing weights of live weight for $\leq 100\%$ ME level diets compared with $> 100\%$ ME levels. Broilers at end of finishing phase (42 d) would require higher maintenance energy (**Em**) because of larger BW. Broilers that consumed treatment diets $\leq 100\%$ ME level utilized major portion of dietary energy in the form of maintenance energy (Em), and thus energy was deficient for optimal protein synthesis. A study conducted in humans showed that FSR and associated synthetic intracellular signaling proteins (insulin-like growth factor 1, protein kinase B, and eukaryotic initiation factor 4E binding protein 1 phosphorylation) were downregulated in response to energy-deficient diet (80% of estimated energy requirements) fed for 10 d, and skeletal FSR was significantly reduced (Pasiakos et al., 2010; Lu et al., 2017). Energy-deficient diets can also affect the ubiquitin-proteasome pathway (of protein degradation), and an ATP-dependent pathway resulting in altered protein degradation.

The excess energy that a broiler consumes is deposited as fat. Heat stress can affect the energy partitioning into either fat deposition or protein deposition. Adipokines such as leptin and adiponectin and their receptors are upregulated during heat stress (Bernabucci et al., 2009; Morera et al., 2012). High energy diets fed to broilers has been shown to increase fat deposition in hyperthermic birds (as compared with high protein diets)

**Table 8.** Percentage of standardized ileal digestible amino acids intake ("as is" basis) of experimental diets in hot season and cool season.

| Amino acid | Lys | Met | Thr | Trp | Arg | Val | Leu | Ile | His | Phe | Cys | Gly | Ser | Pro | Ala | Asp | Glu |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hot season | | | | | | | | | | | | | | | | | |
| Line A | 1.06 | 0.48 | 0.70 | 0.21 | 1.20 | 0.86 | 1.39 | 0.76 | 0.46 | 0.86 | 0.29 | 0.77 | 0.86 | 1.02 | 0.87 | 1.63 | 3.21 |
| Line B | 1.06 | 0.48 | 0.70 | 0.20 | 1.20 | 0.85 | 1.39 | 0.76 | 0.46 | 0.86 | 0.29 | 0.78 | 0.86 | 1.02 | 0.87 | 1.64 | 3.21 |
| *P*-value | 0.82 | 0.99 | 0.72 | 0.48 | 0.43 | 0.95 | 0.64 | 0.80 | 0.70 | 0.79 | 0.81 | 0.44 | 0.76 | 0.82 | 0.65 | 0.73 | 0.76 |
| A,2,800 | 1.12 | 0.49 | 0.74 | 0.23 | 1.27 | 0.91 | 1.41 | 0.80 | 0.49 | 0.90 | 0.31 | 0.83 | 0.91 | 1.04 | 0.90 | 1.75 | 3.42 |
| A,2,925 | 1.06 | 0.56 | 0.68 | 0.20 | 1.20 | 0.83 | 1.33 | 0.74 | 0.45 | 0.84 | 0.29 | 0.75 | 0.85 | 0.98 | 0.83 | 1.58 | 3.18 |
| A,3,050 | 1.03 | 0.48 | 0.70 | 0.20 | 1.15 | 0.83 | 1.34 | 0.73 | 0.44 | 0.83 | 0.27 | 0.77 | 0.81 | 1.01 | 0.85 | 1.54 | 3.12 |
| A,3,175 | 1.03 | 0.44 | 0.66 | 0.20 | 1.16 | 0.82 | 1.41 | 0.73 | 0.46 | 0.86 | 0.28 | 0.74 | 0.84 | 1.02 | 0.87 | 1.57 | 3.12 |
| A,3,300 | 1.06 | 0.42 | 0.73 | 0.19 | 1.21 | 0.89 | 1.45 | 0.79 | 0.47 | 0.89 | 0.29 | 0.77 | 0.89 | 1.04 | 0.89 | 1.72 | 3.20 |
| B,2,800 | 1.12 | 0.49 | 0.74 | 0.23 | 1.27 | 0.90 | 1.40 | 0.80 | 0.47 | 0.89 | 0.32 | 0.82 | 0.90 | 1.03 | 0.90 | 1.73 | 3.40 |
| B,2,925 | 1.09 | 0.58 | 0.72 | 0.21 | 1.24 | 0.87 | 1.39 | 0.76 | 0.47 | 0.87 | 0.32 | 0.81 | 0.89 | 1.04 | 0.87 | 1.68 | 3.30 |
| B,3,050 | 1.04 | 0.48 | 0.71 | 0.19 | 1.16 | 0.84 | 1.35 | 0.73 | 0.44 | 0.84 | 0.28 | 0.77 | 0.82 | 1.02 | 0.85 | 1.55 | 3.13 |
| B,3,175 | 1.02 | 0.43 | 0.66 | 0.20 | 1.16 | 0.81 | 1.41 | 0.73 | 0.46 | 0.84 | 0.27 | 0.74 | 0.83 | 1.02 | 0.87 | 1.57 | 3.10 |
| B,3,300 | 1.03 | 0.41 | 0.69 | 0.19 | 1.18 | 0.86 | 1.41 | 0.76 | 0.46 | 0.87 | 0.27 | 0.75 | 0.87 | 1.01 | 0.86 | 1.67 | 3.12 |
| *P*-value[1] | <.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | <0.0001 | 0.33 | 0.00 | <0.0001 | <0.0001 |
| Cool season | | | | | | | | | | | | | | | | | |
| Line A | 0.79 | 0.43 | 0.51 | 0.19 | 0.89 | 0.63 | 1.14 | 0.61 | 0.35 | 0.68 | 0.16 | 0.53 | 0.62 | 0.85 | 0.67 | 1.17 | 2.66 |
| Line B | 0.74 | 0.42 | 0.45 | 0.18 | 0.82 | 0.53 | 1.04 | 0.56 | 0.32 | 0.61 | 0.19 | 0.45 | 0.56 | 0.77 | 0.60 | 1.02 | 2.43 |
| *P*-value | 0.12 | 0.15 | 0.02 | 0.50 | 0.08 | 0.01 | 0.07 | 0.07 | 0.05 | 0.06 | 0.71 | 0.02 | 0.01 | 0.03 | 0.07 | 0.04 | 0.03 |
| A,2,800 | 0.90 | 0.45 | 0.57 | 0.21 | 0.99 | 0.72 | 1.17 | 0.68 | 0.39 | 0.73 | 0.21 | 0.63 | 0.64 | 0.95 | 0.70 | 1.30 | 2.94 |
| A,2,925 | 0.70 | 0.45 | 0.52 | 0.17 | 0.79 | 0.60 | 0.87 | 0.53 | 0.29 | 0.55 | 0.03 | 0.47 | 0.62 | 0.74 | 0.53 | 0.94 | 2.50 |
| A,3,050 | 0.82 | 0.45 | 0.52 | 0.20 | 0.95 | 0.65 | 1.19 | 0.65 | 0.38 | 0.71 | 0.22 | 0.61 | 0.64 | 0.88 | 0.71 | 1.30 | 2.77 |
| A,3,175 | 0.77 | 0.42 | 0.47 | 0.18 | 0.89 | 0.57 | 1.08 | 0.58 | 0.34 | 0.65 | 0.17 | 0.50 | 0.60 | 0.78 | 0.63 | 1.18 | 2.45 |
| A,3,300 | 0.77 | 0.41 | 0.49 | 0.19 | 0.82 | 0.61 | 1.40 | 0.62 | 0.35 | 0.73 | 0.19 | 0.47 | 0.61 | 0.92 | 0.77 | 1.14 | 2.64 |
| B,2,800 | 0.76 | 0.41 | 0.44 | 0.17 | 0.83 | 0.55 | 0.96 | 0.56 | 0.32 | 0.61 | 0.15 | 0.47 | 0.54 | 0.79 | 0.57 | 1.01 | 2.51 |
| B,2,925 | 0.77 | 0.46 | 0.45 | 0.17 | 0.83 | 0.54 | 0.95 | 0.56 | 0.32 | 0.60 | 0.15 | 0.48 | 0.57 | 0.78 | 0.58 | 0.99 | 2.58 |
| B,3,050 | 0.68 | 0.40 | 0.42 | 0.18 | 0.81 | 0.50 | 0.96 | 0.53 | 0.31 | 0.58 | 0.02 | 0.44 | 0.54 | 0.70 | 0.57 | 0.98 | 2.24 |
| B,3,175 | 0.70 | 0.43 | 0.46 | 0.19 | 0.82 | 0.50 | 0.99 | 0.53 | 0.32 | 0.58 | 0.20 | 0.42 | 0.57 | 0.70 | 0.57 | 1.01 | 2.28 |
| B,3,300 | 0.79 | 0.38 | 0.47 | 0.19 | 0.83 | 0.55 | 1.34 | 0.59 | 0.34 | 0.71 | 0.42 | 0.45 | 0.59 | 0.87 | 0.72 | 1.10 | 2.55 |
| *P*-value[2] | 0.42 | 0.02 | 0.91 | 0.22 | 0.52 | 0.62 | <0.0001 | 0.44 | 0.29 | 0.05 | 0.31 | 0.39 | 0.97 | 0.04 | 0.01 | 0.36 | 0.37 |

[1]Significantly different means existed between dietary ME levels within line in hot season ($P < 0.0001$) for all amino acid analyzed.
[2]*P*-values presented are for combined lines for dietary ME levels. No diet by line interaction was observed.
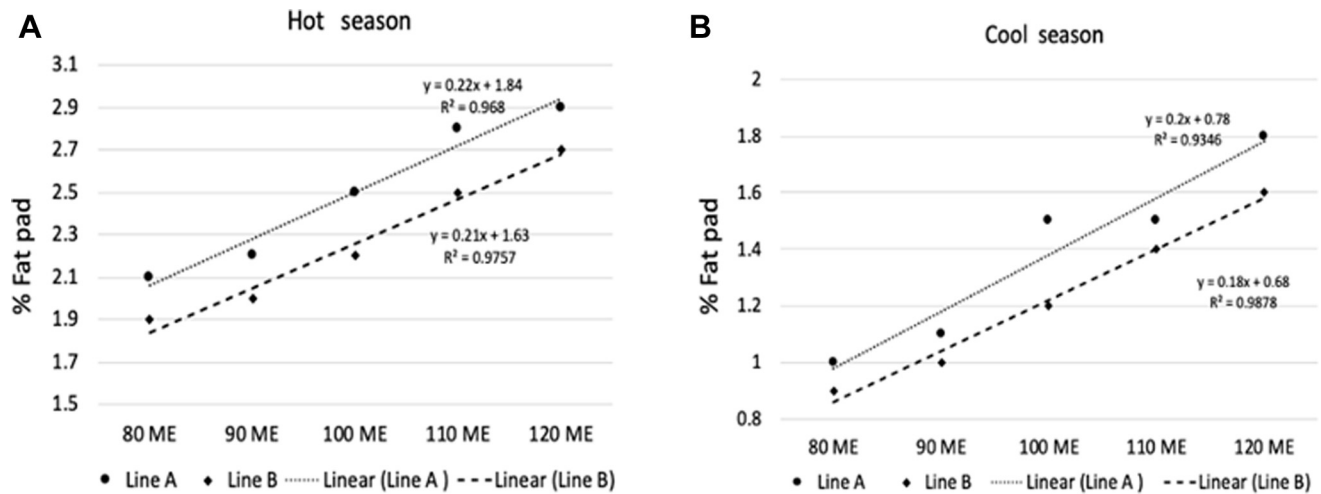
**Figure 5.** *Linear fit of lines for % fat pad of total live weight (A, B) at 42 d for line A and line B for dietary ME levels in hot season and cool season. *80 ME, 90 ME, 100 ME, 110 ME, and 120 ME is equivalent to 2,800, 2,925, 3,050, 3,175, and 3,300 kcal/kg of feed.

(Le Belego et al., 2002) which resonated the findings in the present study with hot season producing increasing % fat pads of BW compared with cool season (Table 7; Figure 5). Line A had higher fat mass than line B in both seasons across all ME levels, indicating higher lipogenesis occurring in line A than line B.

The findings of present study showed that dietary energy levels negatively impacted the FI of both broiler lines linearly ($R^2$ of 0.94 and 0.86 in hot season and cool season, respectively).

Broilers fed lower ME diets consumed more feed to provide the physiological energy requirements resulting in lower feed efficiency. The % fat deposition and % fat pad were positively correlated across dietary ME in both seasons ($R^2 > 0.9$). Line A deposited more % body fat and % fat pad than line B in both seasons ($P < 0.05$). The overall findings suggested that results for performance and yield as affected dietary ME levels were line specific and were affected by grow-out ambient environmental temperatures. The optimal dietary ME level for the ME range studied (2,800–3,000 kcal/kg) at a constant recommended amino acid level lies in determining the best performance and profitability indices by taking into account the grow-out production inputs and processing yield outputs. The industry needs a continuing research aimed at scientific understanding on broiler growth nature and type of gain (protein and fat) in relation to feed energy intake and energy metabolism. The impact dietary energy and amino acid levels have on endocrine function and intermediary metabolism in broilers could shed more light on the fate of these macronutrients and perhaps further understand the effects of these nutrients in feed intake regulation.

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## DISCLOSURES

The authors declare that there is no conflict of interest associated with this article.

## SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://doi.org/10.1016/j.psj.2020.11.062.

## REFERENCES

AOAC International (AOAC). 1990. Official Methods of Analysis, 934.01 for Dry Matter; 982.30 and 985.28 for Amino Acids. Arlington, VA.

AOAC. 1995. Official Methods of Analysis. 16th ed. Association of Official Analytical Chemists, Washington, DC.

Aviagen. 2007. Broiler Nutrition Specifications. Ross 308. Hunstville, AL.

Bergen, W. G. 2008. Measuring in vivo intracellular protein degradation rates in animal systems. J. Anim. Sci. 86:E3–E12.

Bernabucci, U., L. Basirico, P. Morera, N. Lacetera, B. Ronchi, and A. Nardone. 2009. Heat shock modulates adipokines expression in 3T3-L1 adipocytes. J. Mol. Endocrinol. 42:139–147.

Blok, M., and R. Dekker. 2017. Standardized ileal digestibility of amino acids in feedstuffs for poultry. Wageningen Livestock Res. 61:31–35.

Caldas, J. V., K. Hilton, N. Boonsinchai, J. A. England, A. Mauromoustakos, and C. N. Coon. 2018. Dynamics of nutrient utilization, heat production, and body composition in broiler breeder hens during egg production. Poult. Sci. 97:2845–2853.

Carré, B. 2014. Progress in Broiler Selection: Benefits, Limitations, as Assessed by the Digestive Function, and Consequences on Dietary Lysine Concentrations. Pages 189–209 in 14th European Poultry Conference, Stavenger, Norway.

Cheng, T. K., M. L. Hamre, and C. N. Coon. 1997. Responses of broilers to dietary protein levels and amino acid supplementation to low protein diets at various environmental temperatures. J. Appl. Poult. Res. 6:18–33.

Classen, H. L. 2013. Response of broiler chickens to dietary energy and its relationship to amino acid nutrition. Aust. Poult. Sci. Symp. 107–118.

Delezie, E., V. Bruggeman, Q. Swennen, E. Decuypere, and G. Huyghebaert. 2010. The impact of nutrient density in terms of energy and/or protein on live performance, metabolism and carcass composition of female and male broiler chickens of two

commercial broiler strains. J. Anim. Physiol. Anim. Nutr. 94:509–518.

Dozier, III, W., and C. Gehring. 2014. Growth performance of Hubbard× Cobb 500 and Ross× Ross 708 male broilers fed diets varying in apparent metabolizable energy from 14 to 28 days of age. J. Appl. Poult. Res. 23:494–500.

Fan, M. Z., S. W. Kim, T. J. Applegate, and M. Cervantes. 2008. Nonruminant nutrition symposium: understanding protein synthesis and degradation and their pathway regulations. J. Animal Science 86:E1–E2.

Fancher, B. I. 2014. What Is the Upper Limit to Commercially Relevant Body Weight in Modern Broilers? Aviagen, Huntsville, AL.

Fisher, C., and B. J. Wilson. 1974. Pages 151–184 in Energy Requirements of Poultry. Bristish Poultry Science Ltd., Edinburgh, UK.

Gopinger, E., E. Krabbe, D. Surek, L. S. Lopes, and V. Avila. 2017. Live performance, carcass, and bone quality responses of grower and finisher broilers to dietary metabolizable energy levels. Braz. J. Poult. Sci. 19:559–566.

Jackson, S., J. Summers, and S. Leeson. 1982. Effect of dietary protein and energy on broiler performance and production costs. Poult. Sci. 61:2232–2240.

Kyriazakis, I., and G. Emmans. 1992. The effects of varying protein and energy intakes on the growth and body composition of pigs: 1. The effects of energy intake at constant, high protein intake. Br. J. Nutr. 68:603–613.

Le Bellego, L., J. Van Milgen, and J. Noblet. 2002. Effect of high ambient temperature on protein and lipid deposition and energy utilization in growing pigs. Anim. Sci. 75:85–96.

Leeson, S. 2012. Future considerations in poultry nutrition. Poult. Sci. 91:1281–1285.

Leeson, S., L. Caston, and J. Summers. 1996. Broiler response to energy or energy and protein dilution in the finisher diet. Poult. Sci. 75:522–528.

Lemme, A. 2005. Optimum dietary amino acid level for broiler chicken. Pages 117–144 in Simposio Internacional Sobre Exigenscias Nutricionais de Ave E Suisnos.

Liu, S. Y., V. D. Naranjo, P. V. Chrystal, J. Buyse, and P. H. Selle. 2019. Box-Behnken optimisation of growth performance, plasma metabolites and carcass traits as influenced by dietary energy, amino acid and starch to lipid ratios in broiler chickens. PLoS One 14: 0213875.

Lu, Y., J. S. Bradley, S. R. McCoski, J. M. Gonzalez, A. D. Ealy, and S. E. Johnson. 2017. Reduced skeletal muscle fiber size following caloric restriction is associated with calpain-mediated proteolysis and attenuation of IGF-1 signaling. Am. J. Physiol. Regul. Integr. Comp. Physiol. 312:R806–R815.

Maharjan, P., G. Mullenix, K. Hilton, A. Beitia, J. Weil, J. England, D. Martinez, C. Umberson, J. Caldas, D. H. Victor, Naranjo, and C. Coon. 2020a. Effects of dietary amino acid levels and ambient temperature on mixed muscle protein turnover in Pectoralis major during finisher feeding period in two broiler lines. J. Anim. Physiol. Anim. Nutr. 104:1351–1364.

Maharjan, P., G. Mullenix, K. Hilton, A. Beitia, J. Weil, J. Caldas, V. D. N. Haro, and C. Coon. 2020b. Effects of dietary energy levels on Pectoralis major mixed muscle protein turnover and body composition in two broiler lines housed in different grow-out environments. J. Anim. Physiol. Anim. Nutr. In press.

Maharjan, P., G. Mullenix, K. Hilton, J. Caldas, A. Beitia, J. Weil, N. Suesuttajit, A. Kalinowski, N. Yacoubi, V. Naranjo, and J. England. 2020c. Effect of digestible amino acids to energy ratios on performance and yield of two broiler lines housed in different grow-out environmental temperatures. Poult. Sci. 99:6884–6898.

Marchini, C. F., M. B. Café, E. G. Araújo, and M. R. Nascimento. 2016. Physiology, cell dynamics of small intestinal mucosa, and performance of broiler chickens under heat stress: a review. Rev. Colomb. Cienc. Pecu. 29:159–168.

Maynard, C., R. Latham, R. Brister, C. Owens, and S. Rochell. 2019. Effects of dietary energy and amino acid density during finisher and withdrawal phases on live performance and carcass characteristics of Cobb MV× 700 broilers. J. Appl. Poult. Res. 28:729–742.

Morera, P., L. Basirico, K. Hosoda, and U. Bernabucci. 2012. Chronic heat stress up-regulates leptin and adiponectin secretion and expression and improves leptin, adiponectin and insulin sensitivity in mice. J. Mol. Endocrinol. 48:129.

Myers, W. D., P. A. Ludden, V. Nayigihugu, and B. W. Hess. 2004. Technical Note: a procedure for the preparation and quantitative analysis of samples for titanium dioxide. J. Anim. Sci. 82:179–183.

Norton, L. E., and D. K. Layman. 2006. Leucine regulates translation initiation of protein synthesis in skeletal muscle after exercise. J. Nutr. 136:533–537.

Pasiakos, S. M., L. M. Vislocky, J. W. Carbone, N. Altieri, K. Konopelski, H. C. Freake, J. M. Anderson, A. A. Ferrando, R. R. Wolfe, and N. R. Rodriguez. 2010. Acute energy deprivation affects skeletal muscle protein synthesis and associated intracellular signaling proteins in physically active adults. J. Nutr. 140:745–751.

Stipanuk, M. H. 2007. Leucine and protein synthesis: mTOR and beyond. Nutr. Rev. 65:122–129.

Swennen, Q., N. Everaert, M. Debonne, I. Verbaeys, C. Careghi, K. Tona, G. Janssens, E. Decuypere, V. Bruggeman, and J. Buyse. 2010. Effect of macronutrient ratio of the pre-starter diet on broiler performance and intermediary metabolism. J. Anim. Physiol. Anim. Nutr. 94:375–384.

Temim, S., A. M. Chagneau, S. Guillaumin, J. Michel, R. Peresson, P. A. Geraert, and S. Tesseraud. 1999. Effects of chronic heat exposure and protein intake on growth performance, nitrogen retention and muscle development in broiler chickens. Reprod. Nutr. Dev. 39:145–156.

Vieira, S., and C. Angel. 2012. Optimizing broiler performance using different amino acid density diets: what are the limits? J. Appl. Poult. Res. 21:149–155.

Waterlow, J. 1984. Protein turnover with special reference to man. Q. J. Exp. Physiol. 69:409–438.

Zhai, W., E. Peebles, L. Mejia, C. Zumwalt, and A. Corzo. 2014. Effects of dietary amino acid density and metabolizable energy level on the growth and meat yield of summer-reared broilers. J. Appl. Poult. Res. 23:501–515.