Determination of the optimum digestible isoleucine to lysine ratios for male Yield Plus × Ross 708 broilers between 1.0 and 4.0 kg body weight utilizing growth performance and carcass characteristics

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ABSTRACT Three experiments (Exp) were conducted to determine optimal digestible Ile to Lys ratios for male Yield Plus × Ross 708 broilers from approximately 1.0 to 4.0 kg BW. Broilers were fed dose-response diets with inclusions of blood cells that were formulated to contain a gradient of digestible Ile to Lys ratios (0.46 to 0.83). Treatments for Exp 1 to 3 were fed from 21 to 35, 28 to 42, and 35 to 49 d of age, respectively, to target market weights from 2.5 to 4.0 kg. Experiments utilized positive control (PC) diets that did not contain blood cells and were formulated to the same Ile ratios as Treatment 5. Birds and feed were weighed by pen on the first and last days of the experimental period to determine growth performance. Selected broilers were processed and deboned to determine carcass characteristics. For all Exp, quadratic effects (P ≤ 0.001) were observed with BW gain, feed conversion ratio (FCR), breast meat weight, and breast meat yield (BMY) as digestible Ile to Lys ratios increased. Contrasts between PC and Treatment 5 for each Exp displayed no effect of blood cell inclusion with the exception of FCR in Exp 1 (P = 0.001) and BMY in Exp 3 (P = 0.017). Optimum digestible Ile to Lys ratios for Exp 1 were determined to range from 0.640 to 0.725 for growth from 1.0 to 2.5 kg BW (P ≤ 0.001) and breast meat characteristics. In Exp 2, optimum ratios ranged from 0.664 to 0.682 for growth and breast meat characteristics from 1.6 to 3.1 kg BW (P ≤ 0.001). For growth and breast meat characteristics of broilers in Exp 3, optimum ratios ranged from 0.625 to 0.730, from 2.6 to 3.9 kg BW (P ≤ 0.001). Based on these findings, optimum digestible Ile to Lys ratios were determined to range from 0.63 to 0.73 for broilers from 1.0 to 4.0 kg BW.

Key words: isoleucine, ideal ratio, amino acid, broiler

INTRODUCTION

Dietary Ile is the 4th or 5th limiting amino acid (AA) in corn and soybean-meal based diets with inclusions of animal protein meals fed to broilers (Kidd et al., 2000; Corzo et al., 2009). Isoleucine is a member of a subgroup of AA known as branched-chain AA that also includes Val and Leu. The primary function of Ile is contributing to lean tissue development and is a substantial portion of edible tissue (Bae et al., 1999). Isoleucine is reported to play an important role in active immunity and the production of immune cells (Hale et al., 2004; Bender, 2012).

Digestible (dig) Ile requirements and optimum dig Ile to Lys ratios have been reported for broilers up to 1.0 kg BW (Farran and Thomas, 1990; Baker et al., 2002; Barbour and Latshaw, 1992; NRC, 1994; Baker, 1996, 1997). In addition, published research has reported total and dig Ile requirements and optimum dig Ile to Lys ratios for broilers from 1.0 to 3.5 kg BW (NRC, 1994; Baker, 1996; Kidd et al., 2004; Berres et al., 2010; Miranda et al., 2015). However, a disproportionate amount of the existing literature is available for broilers under 1.0 kg BW, and many of these published articles are over 15 yr old. It is now common practice to formulate poultry diets using ideal ratios of limiting AA with Lys as a reference AA (Baker, 2003); however, there is limited published research reporting optimum ratios for dig Ile in broilers greater than 1.0 kg.

Previous research has demonstrated that Ile responses for breast muscle accretion are greater than for growth
(Kidd et al., 2004; Mejia et al., 2011; Dozier et al., 2012). However, published data are sparse reporting optimum dig Ile ratios for growth performance and breast meat yields of broilers grown greater than 2.5 kg. Therefore, determining optimum dig Ile to Lys ratios for broilers from 1.0 to 4.0 kg BW is paramount for accurately formulating broiler diets and optimizing meat yields of broilers across a range of market weights. Objectives of these experiments were to determine the optimum dig Ile to Lys ratios of broilers from 1.0 to 2.5, 1.5 to 3.0, and 2.5 to 4.0 kg BW utilizing responses of growth and carcass parameters.

MATERIALS AND METHODS

All procedures involving live birds were approved by the Auburn University Institutional Animal Care and Use Committee (PRN 2018-3395, PRN 2019-3555, PRN 2020-3655)

Common Procedures

Three experiments (Exp) were conducted utilizing Yield Plus × Ross 708 male broiler chicks (Aviagen North America, Huntsville, AL) obtained from a commercial hatchery at 1 d of age. At the hatchery, all chicks received vaccinations for Marek’s disease, Newcastle disease, and infectious bronchitis. Broiler chicks were placed into floor pens (Exp 1 = 72 pens, 30 birds/pen, 0.11 m²/bird; Exp 2 = 64 pens, 25 birds/pen, 0.09 m²/bird; Exp 3 = 72 pens, 30 birds/pen, 0.11 m²/bird) of a solid-sided house. Each pen was equipped with a tube feeder, a nipple drinker line, and litter from a single previous flock. Experimental facilities consisted of a negative-pressure ventilation system equipped with vent boards, exhaust fans, evaporative cooling pads, and an electronic controller to maintain the temperature and ventilation needs of the birds. House temperature at chick placement was maintained at 33°C and was gradually reduced to 20°C at d 21 to maintain bird comfort. The photoperiod was set at 23L:1D for the first 7 d posthatch and 20L:4D was maintained for the duration of the Exp. Light intensity was set at 30, 10, and 5 lux from 1 to 7, 8 to 14, and 15 d of age through the duration of the Exp, respectively. Feed and water were provided ad libitum throughout the experimental periods. Broiler chicks were fed common starter and grower diets until the beginning of the experimental periods (Exp 1 = 1 to 20 d of age; Exp 2 = 1 to 14 and 15 to 27 d of age; Exp 3 = 1 to 18 and 19 to 34 d of age), formulated to meet or exceed the nutrient recommendations of the NRC (1994) (Table 1). The incidence of mortality was recorded daily throughout each Exp.

Dietary Treatments

Amino acid analysis of corn, soybean-meal, and spray-dried blood cells are presented in Table 2. Corn and soybean meal were analyzed using near infrared reflective spectroscopy (Evonik Nutrition AMINONIR®) to determine dig AA concentrations. Blood cells (American Protein Corporation, Arion, IA) were analyzed via HPLC (method 982.30 E (a,b,c); AOAC International, 2006) to determine the total AA content. Digestible AA content of the blood cells was determined by multiplying the total AA concentrations by digestibility coefficients adapted from the Brazilian Tables for Poultry and Swine (2017). Different batches of corn, soybean meal, and blood cells were used in each experiment (Table 2). Blood cells were used due to their low concentration of dig Ile (0.40 to 0.75%) relative to the other indispensable AA. This enabled a small inclusion of blood cells to create a dig Ile deficient test diet (Negative Control).

In Exp 1, 2, and 3, dig Ile to Lys ratios of titrated diets were formulated to range from 0.48 to 0.83, 0.46 to 0.82, and 0.48 to 0.83, respectively (Table 3). Experimental diets were created by the mixing of negative control (NC) (deficient in dig Ile) and summit (excess dig Ile) diets in varying proportions. Each experimental diet was formulated to contain 95% of the recommended digestible Lys concentration to prevent birds from overconsuming Lys (Baker and Han, 1994; NRC, 1994). For Exp 1, the NC diet was formulated to contain 0.50% dig Ile and excess dig Lys.
1.05% dig Lys, and the summit was formulated to contain 0.87 and 1.05% dig Ile and Lys, respectively. Treatments 1 to 8 contained 100.0, 85.7, 71.4, 57.1, 42.9, 28.6, 14.3, 0.0% NC diet, respectively, and the remaining portion of each treatment (Trt) was comprised of the summit diet. In Exp 2, the NC diet was formulated to contain 0.44% dig Ile and 0.95% dig Lys, and the summit diet was formulated to contain 0.78% dig Ile and 0.95% dig Lys. Diets were consisted of 100.0, 83.3, 66.7, 50.0, 33.3, 16.7, 0.0% NC diet for Trt 1 to 7, respectively, and the summit diet comprised the remainder. In Exp 3, the NC diet was formulated to contain 0.42 and 0.87% dig Ile and Lys, respectively, and the summit diet was formulated to contain 0.72 and 0.87% dig Ile and Lys, respectively. Treatments 1 to 8 contained 100.0, 85.7, 71.4, 57.1, 42.9, 28.6, 14.3, 0.0% NC diet, respectively, and the remainder was made up of summit diet. All Exp had a positive control (PC) (Exp 1 = Trt 9; Exp 2 = Trt 8; Exp 3 = Trt 9) that was formulated without blood cells to have the same dig Ile to Lys ratio as Trt 5. For Exp 1, 2, and 3, PC diets were formulated to contain dig Ile to Lys ratios of 0.68, 0.70, and 0.68, respectively.

**Measurements**

Birds and feed were weighed by pen at the beginning and end of each experimental period (Exp 1 = 21 and 35 d of age; Exp 2 = 28 and 42 d of age; Exp 3 = 35 and 49 d of age) in order to determine BW gain (BWG), feed intake (FI), and feed conversion ratio (FCR). At the end of each experimental period (Exp 1 = d 36; Exp 2 = d 43; Exp 3 = d 50), birds were randomly selected to be processed to assess carcass characteristics (Exp 1 = 9 birds/pen; Exp 2 = 14 birds/pen; Exp 3 = 14 birds/pen). Birds were processed in a pilot processing facility at the Auburn University Poultry Research Unit following a 12-h feed withdrawal period. Broilers were electronically stunned, exsanguinated, scalded, picked mechanically, eviscerated mechanically, and placed on ice. Carcasses were chilled in ice water for a period of 3 h.

**Table 2.** Analysis of amino acid and crude protein concentrations of primary ingredients used in the formulation of diets fed to Yield Plus × Ross 708 male broilers from 1.0 to 4.0 kg body mass.

| Nutrient, % “as fed” | Corn | SBM<sup>1</sup> | Blood Cells<sup>2</sup> |
|----------------------|------|------------------|------------------------|
|                      | Total<sup>4</sup> | Dig<sup>4</sup> | Total<sup>5</sup> | Dig<sup>5</sup> | Total<sup>6</sup> | Dig<sup>6</sup> |
| Crude protein        | 7.95 | —                | 43.86                  | —                | 96.75                  | —                |
| SAA                  | 0.370 | 0.329            | 1.220                  | 1.015            | 1.820                  | 1.638            |
| Lys                  | 0.260 | 0.219            | 2.710                  | 2.350            | 9.240                  | 8.316            |
| Thr                  | 0.290 | 0.244            | 1.750                  | 1.440            | 4.400                  | 3.960            |
| Val                  | 0.400 | 0.359            | 2.160                  | 1.827            | 9.100                  | 8.190            |
| Ile                  | 0.290 | 0.257            | 2.000                  | 1.814            | 0.410                  | 0.369            |
| Trp                  | 0.080 | 0.067            | 0.600                  | 0.521            | 1.680                  | 1.512            |
| Arg                  | 0.380 | 0.337            | 3.090                  | 2.818            | 3.600                  | 3.240            |
| His                  | 0.230 | 0.214            | 1.120                  | 0.993            | 6.410                  | 5.769            |
| Phe                  | 0.400 | 0.367            | 2.210                  | 1.960            | 7.540                  | 6.786            |
| Leu                  | 0.970 | 0.895            | 3.370                  | 2.956            | 13.000                 | 11.700           |
|                      | 8.50 | —                | 47.75                  | —                | 93.67                  | —                |
| SAA                  | 0.335 | 0.281            | 1.250                  | 1.062            | 1.736                  | 1.562            |
| Lys                  | 0.261 | 0.201            | 2.802                  | 2.518            | 8.518                  | 7.667            |
| Thr                  | 0.273 | 0.216            | 1.798                  | 1.528            | 4.196                  | 3.776            |
| Val                  | 0.364 | 0.309            | 2.118                  | 1.964            | 7.783                  | 7.005            |
| Ile                  | 0.261 | 0.225            | 2.077                  | 1.807            | 0.833                  | 0.750            |
| Trp                  | 0.047 | 0.039            | 0.672                  | 0.584            | 1.587                  | 1.428            |
| Arg                  | 0.375 | 0.326            | 3.358                  | 2.955            | 3.364                  | 3.028            |
| His                  | 0.205 | 0.174            | 1.178                  | 1.013            | 5.776                  | 5.198            |
| Phe                  | 0.341 | 0.303            | 2.438                  | 2.170            | 6.343                  | 5.709            |
| Leu                  | 0.898 | 0.826            | 3.593                  | 3.145            | 11.820                 | 10.638           |
|                      | 7.11 | —                | 46.56                  | —                | 90.00                  | —                |
| SAA                  | 0.320 | 0.278            | 1.260                  | 1.064            | 1.990                  | 1.710            |
| Lys                  | 0.240 | 0.197            | 2.820                  | 2.482            | 8.520                  | 7.668            |
| Thr                  | 0.255 | 0.209            | 1.780                  | 1.495            | 4.200                  | 3.780            |
| Val                  | 0.340 | 0.299            | 2.200                  | 1.936            | 5.000                  | 4.500            |
| Ile                  | 0.245 | 0.216            | 2.110                  | 1.836            | 0.690                  | 0.621            |
| Trp                  | 0.055 | 0.042            | 0.630                  | 0.554            | 1.450                  | 1.305            |
| Arg                  | 0.360 | 0.317            | 3.350                  | 3.015            | 3.400                  | 3.060            |
| His                  | 0.210 | 0.189            | 1.200                  | 1.056            | 5.580                  | 5.265            |
| Phe                  | 0.330 | 0.297            | 2.380                  | 2.118            | 6.860                  | 6.174            |
| Leu                  | 0.830 | 0.772            | 3.500                  | 3.080            | 12.110                 | 10.899           |

1Soybean meal.
2American Protein Corporation, Arion, IA.
3Broilers in were fed experimental diets from 21 to 35, 28 to 42, and 35 to 49 d of age for Experiments 1, 2, and 3, respectively.
4Digestible values determined using Evonik Nutrition AMINONIR<sup>®</sup> near infrared reflective spectroscopy.
5Values obtained from HPLC analysis of ingredients (method 982.30 E (a,b,c); AOAC International, 2006).
6Values obtained by multiplying total amino acid concentrations by digestibility coefficients adapted from the Brazilian Tables (2017) for blood cells.
Table 3. Ingredient and nutrient composition of dietary treatments fed to Yield Plus × Ross 708 male broilers from 1.0 to 4.0 kg body mass.

| Ingredient, % “as-fed” | Experiment 1 | Experiment 2 | Experiment 3 |
|------------------------|--------------|--------------|--------------|
|                        | NC           | Summit       | PC           | NC           | Summit       | PC           |
| Corn                   | 76.25        | 76.07        | 62.46        | 79.10        | 78.95        | 64.28        |
| Soybean meal           | 15.32        | 15.52        | 29.99        | 12.92        | 12.52        | 28.81        |
| Soybean oil            | 0.45         | 0.25         | 3.12         | 0.45         | 0.25         | 3.57         |
| Limestone              | 0.67         | 0.67         | 0.68         | 0.66         | 0.66         | 0.67         |
| Defluorinated phosphate| 1.00         | 1.00         | 0.98         | 1.49         | 1.49         | 1.29         |
| Sodium bicarbonate     | 0.27         | 0.27         | 0.29         | 0.34         | 0.34         | 0.32         |
| Salt, NaCl             | 0.18         | 0.18         | 0.21         | 0.17         | 0.17         | 0.23         |
| DL-Methionine          | 0.43         | 0.43         | 0.35         | 0.39         | 0.39         | 0.30         |
| L-Lysine, HCl          | 0.40         | 0.40         | 0.27         | 0.40         | 0.40         | 0.12         |
| AU Trace mineral premix| 0.10         | 0.10         | 0.10         | 0.10         | 0.10         | 0.10         |
| L-Threonine            | 0.23         | 0.23         | 0.15         | 0.23         | 0.23         | 0.09         |
| AU vitamin premix      | 0.08         | 0.08         | 0.08         | 0.08         | 0.08         | 0.08         |
| Phytase                | 0.01         | 0.01         | 0.01         | 0.01         | 0.01         | 0.01         |
| L-Val                  | 0.11         | 0.11         | 0.09         | 0.16         | 0.16         | 0.05         |
| L-Ile                  | 0.01         | 0.38         | —            | 0.01         | 0.36         | —            |
| L-Trp                  | 0.05         | 0.05         | 0.01         | 0.08         | 0.08         | 0.01         |
| L-Arg                  | 0.60         | 0.60         | 0.31         | 0.42         | 0.42         | 0.06         |
| Gly                    | 0.68         | 0.69         | 0.41         | 0.50         | 0.50         | 0.09         |
| Blood cells            | 2.50         | 2.50         | —            | 2.00         | 2.00         | —            |
| Titanium dioxide       | 0.50         | 0.50         | —            | 0.50         | 0.50         | —            |

Calculated analyses, % (unless otherwise noted):

- AME, kcal/kg
- Crude protein
- Digestible Lys
- Digestible SAA
- Digestible Thr
- Digestible Val
- Digestible Ile
- Digestible Leu
- Ca
- Nonphosphate P
- Analyzable P
- Na

1Experimental diets 1 to 8 for experiments 1 and 3 contained 100.0, 85.7, 51.4, 42.9, 28.6, 14.3, 0.0% NC diet, respectively and diets 1 to 7 in experiment 2 contained 100.0, 83.3, 66.7, 50.0, 33.3, 16.7, 0.0% NC diet, respectively and remaining space in all diets was comprised of summit diet to create diets of intermediate digestible Ile to Lys ratios.

2Broilers were fed experimental diets from 21 to 35, 28 to 42, and 35 to 49 d of age for Experiments 1, 2, and 3, respectively, in 8 replications/treatment.

3Negative control.

4Positive control diets formulated to have a digestible Ile to Lys ratio of 0.68, 0.70, and 0.68 for Experiments 1, 2, and 3, respectively.

5Trace mineral premix include per kg of diet: Mn (manganese sulfate), 120 mg; Zn (zinc sulfate), 100 mg; Fe (iron sulfate monohydrate), 30 mg; Cu (trisacetyl copper chlorde), 8 mg; I (ethylenediamine dihydriodide), 1.4 mg; and Se (sodium selenite), 0.3 mg.

6American Protein Corporation, Arion, IA.

7Quantum Blue Phytase, AB Vista, Marlborough, UK.

8American Protein Corporation, Arion, IA.

9Positive control diets formulated to have a digestible Ile to Lys ratio of 0.68, 0.70, and 0.68 for Experiments 1, 2, and 3, respectively.

10Sulfur Amino Acids.

11Analyzed digestible Lys concentrations were 0.94 and 0.92, 0.94 and 0.92, and 0.92 and 0.84% for negative control and summit diets of Experiments 1 to 3, respectively.

12Positive control diets formulated to have a digestible Ile to Lys ratio of 0.68, 0.70, and 0.68 for Experiments 1, 2, and 3, respectively.

13Analyzed digestible Ile concentrations were 0.94 and 0.92, 0.94 and 0.92, and 0.92 and 0.84% for negative control and summitt diets of Experiments 1 to 3, respectively.

14Analyzed digestible Ile concentrations were 0.94 and 0.92, 0.94 and 0.92, and 0.92 and 0.84% for negative control and summit diets of Experiments 1 to 3, respectively.

and then drained of excess water for approximately 3 min. The abdominal fat pad was removed and weighed separately from the chilled carcass to determine the fat percentage. Carcasses were deboned the following day to obtain breast fillets (pectoralis major), tenders (pectoralis minor), wings, drums, and boneless-skinless thigh meat by experienced personnel utilizing stationary cones (Exp 1). For Exp 2 and 3, breast fillets and tenders were weighed. Tender and breast fillet weights were combined for the analysis of total breast meat weight. Meat yield percentages were based on live weight at 35, 42, and 49 d of age for Exp 1, 2, and 3, respectively.

**Apparent Ileal Amino Acid Digestibility Assays**

For all Exp, apparent ileal AA digestibility was determined for the NC and summit diets. At 38, 45, and 52 d of age for Exp 1, 2 and 3, respectively, ileal digesta was collected from 6 birds per pen from the NC and summit Trt (Exp 1 = treatments 1 and 8; Exp 2 = treatments 1 and 7; Exp 3 = treatments 1 and 8). Birds were euthanized via CO2 asphyxiation and digesta was collected by gently flushing a section of the terminal ileum (terminal 1/3 between the Meckel’s diverticulum and 2 cm of the ileum) with 30 mL of 0.9% NaCl solution at 3, 6, and 9°C.
 proximal to the ileo-cecal junction) with deionized water. Diets and digesta were lyophilized in a Virtis Genesis Pilot Lyophilizer (SP Industries, Warminster, PA), and then ground in an electric coffee grinder (Hamilton Beach, Glen Allen, VA). The dried digesta was analyzed in duplicate and dried diets were analyzed in quadruplicate for TiO$_2$ concentration using the method described by Short et al. (1996). Absorbance was measured on a spectrophotometer (SPECTRAMax Plus 384, Molecular Devices, Sunnyvale, CA), using 1.0 mL of solution in a cuvette reader. A standard curve was used to create a regression equation ($R^2 = 0.991, 0.985, 0.990$ for Exp 1, 2, and 3, respectively) as a reference for TiO$_2$ concentration in diets and digesta. Digesta and diet samples were also analyzed in duplicate for AA profile using HPLC (method 982.30 E (a,b,c); AOAC International, 2006). These values were used to calculate apparent ileal AA digestibility using the following formula:

$$\text{AIAAD} = \left[ 1 - \left( \frac{T_i}{T_o} \right) \times \left( \frac{AA_{o}}{AA_{i}} \right) \right] \times 100$$

where $T_i$ represents the TiO$_2$ concentration in the input (diet), $T_o$ represents the TiO$_2$ concentration in the output (digesta), $AA_{o}$ represents the concentration of the AA in the output, and $AA_{i}$ represents the concentration of the AA in the input (Dilger et al., 2004).

### RESULTS AND DISCUSSION

For Exp 1, analyzed dig Lys and Ile values of test diets were lower than the formulated concentrations (Table 4). For Exp 2, analyzed dig Lys values for the test diets were in agreement with the calculated values as was the dig Ile concentration of the summit; however, analyzed values for Ile in the NC were lower than formulated (Table 4). Analyzed dig Lys concentrations for Exp 3 were in agreement with calculated values as was the dig Ile concentration in the NC; however, the analyzed Ile concentration of the summit was lower than formulated. These discrepancies in analyzed dig Ile values may be attributed to the lower digestibility coefficients of the NC diets as Table 4 illustrates that the digestibility coefficients of Ile are considerably lower for

### Statistical Analysis

All 3 Exp were conducted as a randomized complete block design with pen location as the blocking factor and 8 replications/trt. Pen was considered the experimental unit. Regression analysis and contrasts were performed with the PROC REG and PROC MIXED procedures of SAS 9.4 (2017). The dose response dietary Trt (Exp 1 = 1 to 8; Exp 2 = 1 to 7; Exp 3 = 1 to 8) were delineated for optimum dig Ile to Lys ratios using linear and quadratic regression. For all Exp, a contrast was performed between the PC and Trt as these diets were formulated to contain the same dig Lys ratios using linear and quadratic regression. For these analyses, mortality was arcsine square root transformed. The determination of the optimum ratios for all Exp was performed via linear and quadratic broken-line regression using Programa Prático de Modelagem (Garcia-neto and Perri, 2015) on the dose response diets. For all statistical processes, significance was considered at $P$-value $\leq 0.05$.  

### Table 4. Amino acid digestibility for male Yield Plus × Ross 708 broilers fed negative control and summit diets from 1.0 to 4.0 kg body mass$^1$.  

| Amino acid | Experiment 1$^2$ | Experiment 2 | Experiment 3 |
|------------|-----------------|--------------|--------------|
|            | NC$^3$          | Summit$^4$   | NC$^3$       | Summit$^4$   |
|            | DC$^5$ dig AA$^6$ | DC dig AA    | DC$^5$ dig AA | DC dig AA    |
|            | %               | %            | %            | %            |
| Lys        | 89.85           | 1.01         | 89.73        | 1.00         |
| SAA$^7$    | 88.69           | 0.70         | 88.51        | 0.70         |
| Thr        | 82.40           | 0.66         | 82.55        | 0.66         |
| Val        | 85.82           | 0.77         | 85.36        | 0.72         |
| Ile        | 80.91           | 0.45         | 86.99        | 0.72         |
| Trp        | 83.21           | 0.18         | 82.21        | 0.18         |
| Arg        | 93.31           | 1.30         | 92.78        | 1.29         |
| Leu        | 86.79           | 1.32         | 87.31        | 1.33         |
| Phe        | 88.13           | 0.78         | 87.31        | 0.75         |
| His        | 88.19           | 0.43         | 87.27        | 0.42         |

$^1$Experimental diets 1 to 8 for experiments 1 and 3 contained 100.0, 85.7, 71.4, 57.1, 42.9, 28.6, 14.3, 0.0% NC diet, respectively and diets 1 to 7 in experiment 2 contained 100.0, 83.3, 66.7, 50.0, 33.3, 16.7, 0.0% NC diet, respectively, and remaining space in all diets was comprised of summit diet to create diets of intermediate digestible Ile to Lys ratios.

$^2$Broilers were fed experimental diets from 21 to 35, 28 to 42, and 35 to 49 d of age for Experiment 1, Experiment 2, and Experiment 3, respectively in 8 replications/treatment.

$^3$Negative control diets were formulated to contain 1.05% Lys and 0.50% Ile; 0.95% Lys and 0.44% Ile; and 0.87% Lys and 0.42% Ile on a digestible basis for Experiments 1 to 3, respectively.

$^4$Summit diets were formulated to contain 1.05% Lys and 0.87% Ile; 0.95% Lys and 0.78% Ile; and 0.87% Lys and 0.72% Ile on a digestible basis for Experiments 1 to 3, respectively.

$^5$Digestibility coefficient, obtained by titanium dioxide assay according to method of Short et al. (1996).

$^6$Concentration of digestible amino acid included in the diet. Obtained by multiplying total amino acid concentration from HPLC analysis by the digestibility coefficient.

$^7$Sulfur Amino Acids.
Table 5. Growth performance of male Yield Plus × Ross 708 broilers fed varying digestible Ile to Lys ratios from 1.0 to 2.5 kg BW (21 to 35 d of age).\(^1\)

| Dietary treatments\(^2\) | BW (kg) \(^3\) | BWG (kg) \(^3\) | FI \(^4\) (mg/d) | Dig Ile Intake \(^5\) (kg/kg) | FCR \(^6\) (%) | Mortality |
|--------------------------|----------------|----------------|----------------|--------------------------------|---------------|-----------|
| 1) dIle:Lys ratio 0.44   | 2.063          | 1.082          | 2.051          | 613                            | 1.897         | 0.42      |
| 2) dIle:Lys ratio 0.49   | 2.199          | 1.198          | 2.123          | 679                            | 1.772         | 0.86      |
| 3) dIle:Lys ratio 0.54   | 2.389          | 1.355          | 2.254          | 766                            | 1.663         | 0.86      |
| 4) dIle:Lys ratio 0.59   | 2.451          | 1.437          | 2.302          | 852                            | 1.602         | 0.00      |
| 5) dIle:Lys ratio 0.64   | 2.498          | 1.484          | 2.334          | 935                            | 1.573         | 0.83      |
| 6) dIle:Lys ratio 0.70   | 2.467          | 1.465          | 2.283          | 964                            | 1.551         | 0.83      |
| 7) dIle:Lys ratio 0.75   | 2.471          | 1.459          | 2.292          | 963                            | 1.536         | 0.00      |
| 8) dIle:Lys ratio 0.81   | 2.490          | 1.493          | 2.190          | 963                            | 1.515         | 1.82      |
| 9) Positive control (PC)\(^7\) | 2.473          | 1.446          | 2.190          | 963                            | 1.515         | 1.82      |

**Regression analysis**

- **Linear**
  - PC vs. Trt 5: 0.33, 0.08, 0.001, 0.022, 0.001, 0.001
  - R\(^2\) linear: 0.673, 0.711, 0.395, 0.968, 0.782, 0.005
  - Coefficient of Determination: 0.72, 0.74

- **Quadratic**
  - PC vs. Trt 5: 0.33, 0.08, 0.001, 0.022, 0.001, 0.74
  - R\(^2\) quadratic: 0.848, 0.905, 0.648, 0.972, 0.944, 0.010

**Proportunities**

- Probabilities: 0.001, 0.59, 0.001, 0.77, 0.18

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1. Values represent least-square means for 8 replicate pens with 30 chicks per pen at 35 d of age. Experiment 1.
2. Treatments 1 to 8 are represented by calculated digestible Ile to Lys ratios.
3. Body weight gain.
4. Feed intake.
5. Determined using digestible Ile concentration of each treatment.
6. Feed conversion ratio corrected for mortality.
7. Calculated digestible Ile to Lys ratio = 0.68.
8. Pooled standard error.

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Table 6. Carcass characteristics of male Yield Plus £ Ross 708 broilers fed diets with increasing digestible Ile to Lys ratios from 1.0 to 2.5 kg BW (21 to 35 d of age).1

| Dietary treatments2 | BW kg | Weight breast meat kg | Yield % | Weight wing kg | Yield % | Weight drum kg | Yield % | Weight thigh meat kg | Yield % | Weight abdominal fat kg | Yield % |
|---------------------|-------|-----------------------|---------|----------------|---------|----------------|---------|-----------------------|---------|------------------------|---------|
| 1) dIle:Lys ratio 0.44 | 2.063 | 1.500 | 72.69 | 0.466 | 22.57 | 0.161 | 7.79 | 0.198 | 9.60 | 0.206 | 9.98 | 0.021 | 1.36 |
| 2) dIle:Lys ratio 0.49 | 2.199 | 1.598 | 72.67 | 0.514 | 23.30 | 0.168 | 7.66 | 0.206 | 9.40 | 0.216 | 9.81 | 0.021 | 1.33 |
| 3) dIle:Lys ratio 0.54 | 2.389 | 1.754 | 73.45 | 0.581 | 24.32 | 0.180 | 7.54 | 0.215 | 9.01 | 0.232 | 9.71 | 0.021 | 1.33 |
| 4) dIle:Lys ratio 0.59 | 2.451 | 1.799 | 73.38 | 0.610 | 24.86 | 0.189 | 7.71 | 0.223 | 9.82 | 0.237 | 9.61 | 0.021 | 1.33 |
| 5) dIle:Lys ratio 0.64 | 2.498 | 1.855 | 74.25 | 0.581 | 24.32 | 0.180 | 7.54 | 0.215 | 9.01 | 0.232 | 9.71 | 0.021 | 1.33 |
| 6) dIle:Lys ratio 0.70 | 2.467 | 1.820 | 73.77 | 0.644 | 26.30 | 0.200 | 7.66 | 0.223 | 9.00 | 0.232 | 9.36 | 0.020 | 1.08 |
| 7) dIle:Lys ratio 0.75 | 2.471 | 1.820 | 73.77 | 0.644 | 26.30 | 0.200 | 7.66 | 0.223 | 9.00 | 0.232 | 9.36 | 0.020 | 1.08 |
| 8) dIle:Lys ratio 0.81 | 2.473 | 1.836 | 74.21 | 0.638 | 25.77 | 0.194 | 7.83 | 0.223 | 9.00 | 0.232 | 9.36 | 0.015 | 1.08 |
| 9) Positive control (PC)3 | 2.473 | 1.836 | 74.21 | 0.638 | 25.77 | 0.194 | 7.83 | 0.223 | 9.00 | 0.232 | 9.36 | 0.015 | 1.08 |

SEM4

| Regression analysis | Linear | Quadratic | Contrast |
|---------------------|---------|-----------|----------|
| PC vs. Trt 5 | 0.001 | 0.001 | 0.001 |
| Probability | 0.001 | 0.001 | 0.001 |
| Coefficient of Determination | R2 linear | R2 quadratic | R2 quadratic |
| Experiments | 0.586 | 0.671 | 0.622 | 0.668 | 0.685 | 0.713 | 0.806 | 0.796 | 0.785 | 0.350 | 0.723 | 0.495 | 0.570 | 0.644 | 0.518 | 0.252 | 0.14 | 0.01 |
| 1Values are least-square means of 8 replicate pens, with 9 birds/pen being selected and processed at d 35. Experiment 1. |
| 2Treatments 1 to 8 are represented by calculated digestible Ile to Lys ratios. |
| 3Calculated digestible Ile to Lys ratio = 0.68. |
| 4Pooled standard error. |

Table 7. Optimal digestible Ile to Lys ratios for male Yield Plus £ Ross 708 broilers based on growth performance and carcass characteristics from 1.0 to 4.0 kg body mass.

| Response | Estimated ratio1 | 95% CI2 | SEM3 | R2 (%) | P-value4 |
|----------|-----------------|---------|-------|--------|--------|
| Experiment 1 | | | | | |
| Linear | | | | | |
| BWG5, kg | 0.600 | 0.586 to 0.612 | 0.006 | 92.27 | <0.001 |
| FCR, kg:kg | 0.605 | 0.594 to 0.617 | 0.007 | 93.54 | <0.001 |
| TBMW6, kg | 0.622 | 0.601 to 0.644 | 0.011 | 87.17 | <0.001 |
| TBMY7, % | 0.668 | 0.637 to 0.699 | 0.016 | 81.35 | <0.001 |
| Quadratic | | | | | |
| BWG, kg | 0.668 | 0.639 to 0.697 | 0.015 | 92.07 | <0.001 |
| FCR, kg:kg | 0.671 | 0.627 to 0.701 | 0.019 | 91.90 | <0.001 |
| TBMW, kg | 0.664 | 0.627 to 0.701 | 0.019 | 91.90 | <0.001 |
| TBMY, % | 0.682 | 0.590 to 0.775 | 0.047 | 92.28 | <0.001 |
| Experiment 2 | | | | | |
| Linear | | | | | |
| BWG, kg | 0.665 | 0.609 to 0.722 | 0.029 | 96.03 | <0.001 |
| FCR, kg:kg | 0.671 | 0.617 to 0.725 | 0.028 | 96.66 | <0.001 |
| TBMW, kg | 0.664 | 0.627 to 0.701 | 0.019 | 91.90 | <0.001 |
| TBMY, % | 0.682 | 0.590 to 0.775 | 0.047 | 92.28 | <0.001 |
| Quadratic | | | | | |
| BWG, kg | 0.802 | 0.621 to 0.984 | 0.092 | 91.46 | <0.001 |
| FCR, kg:kg | 0.808 | 0.644 to 0.979 | 0.083 | 92.58 | <0.001 |
| TBMW, kg | 0.783 | 0.649 to 0.917 | 0.068 | 95.86 | <0.001 |
| TBMY, % | 0.755 | 0.550 to 0.959 | 0.104 | 88.35 | 0.002 |
| Experiment 3 | | | | | |
| Linear8 | | | | | |
| BWG, kg | 0.625 | 0.568 to 0.683 | 0.029 | 96.83 | <0.001 |
| FCR, kg:kg | 0.692 | 0.623 to 0.762 | 0.035 | 91.92 | <0.001 |
| TBMW, kg | 0.694 | 0.623 to 0.765 | 0.036 | 91.90 | <0.001 |
| TBMY, % | 0.730 | 0.652 to 0.807 | 0.039 | 92.81 | <0.001 |

1Values obtained using linear and quadratic broken-line modelling. |
295% confidence intervals for the optimal digestible Ile to Lys ratios. |
3Standard error of the estimate. |
4Broilers in were fed experimental diets from 21 to 35, 28 to 42, and 35 to 49 d of age for Experiments 1, 2, and 3, respectively. |
5Total breast meat weight. |
6Total breast meat yield. |
7Quadratic broken-line regression did not fit the data for Experiment 3 and yielded insignificant results.
required to obtain optimum growth responses in modern broiler strains. Elevated concentrations of dig Ile increased meat yields for all carcass parts except for wings. The inclusion of blood cells to Trt 5 may have caused an elevated FI response relative to the PC. There was no effect on the growth rate of the broilers, thus the lower FI caused broilers provided the PC to have a lower FCR than those fed Trt 5. Birds fed Trt 5 had lower daily dig Ile intakes when compared with the broilers consuming the PC even with the greater FI of birds caused by Trt 5 containing a lower concentration of dig Ile than it was formulated to contain. There were also differences observed for abdominal fat weight and yield, with broilers provided Trt 5 having the greater responses for these parameters relative to the PC. This may be due to broilers fed Trt 5 having a greater FI and a larger nutrient intake than birds provided the PC.

Optimum dig Ile to Lys ratios were 0.67 and 0.69 for BWG and BMW, respectively, above a previously reported optimum of 0.65 for broilers from 14 to 35 d of age (Berres et al., 2010). The optimum dig Ile to Lys ratio obtained for BMW of 0.71 is also greater than previously reported optimum dig Ile ratios for broilers in this age range (Baker et al., 2002; Baker, 1997). In other research, broilers of larger weight classes displayed estimates of optimum ratios that were greater for breast meat yield than for BWG (Mejia et al., 2011; Miranda et al., 2015). Mejia et al. (2011) reported an optimum dig Ile to Lys ratio of 0.72 for BMY, however, these data evaluated broilers from 1.5 to 3.1 kg BW. These data are in agreement with the value obtained in the present Exp for BMW, but the optimum Ile ratio for BMY was found to be lower at 0.67. This lower value for breast yield may be due to the relative size of the broilers, not showing a difference in the dig Ile need between breast yield and growth.

Quadratic broken-line regression was used to determine optimum Ile ratios for BWG, FCR, and BMW. Both quadratic and linear broken-line models produced good fits to the data, with very similar standard errors and confidence intervals. The quadratic models were chosen for these parameters as when both linear and quadratic models are fit to curvilinear data the linear model can underestimate the optimum response (Robbins et al., 2006). The linear model was chosen to estimate the optimum ratio for BMY, as it produced a much lower standard error (0.016 vs. 0.043) and therefore a smaller 95% confidence interval. This may have occurred because there were not adequate additional data points above the break point of the fit line causing an over estimation of the optimum ratio with the quadratic model. Based on these data, an optimal dig Ile to Lys ratio of 0.67 to 0.69 is likely appropriate for broilers from 1.0 to 2.5 kg BW.

### Table 8. Growth performance of male Yield Plus × Ross 708 broilers fed varying digestible Ile to Lys ratios from 1.6 to 3.1 kg BW (28 to 42 d of age)

| Dietary treatments | BW (kg) | BWG (kg) | FI (kg) | Dig Ile Intake (mg/d) | FCR (kg/kg) | Mortality (%) |
|-------------------|--------|---------|--------|----------------------|------------|--------------|
| 1) dIle:Lys ratio 0.42 | 2.732 | 1.178 | 2.279 | 903 | 1.940 | 4.0 |
| 2) dIle:Lys ratio 0.49 | 2.735 | 1.195 | 2.286 | 1.232 | 1.920 | 4.0 |
| 3) dIle:Lys ratio 0.56 | 2.939 | 1.377 | 2.436 | 1.437 | 1.771 | 3.5 |
| 4) dIle:Lys ratio 0.63 | 3.063 | 1.486 | 2.536 | 1.516 | 1.707 | 1.0 |
| 5) dIle:Lys ratio 0.69 | 3.117 | 1.521 | 2.533 | 1.718 | 1.665 | 1.0 |
| 6) dIle:Lys ratio 0.76 | 3.144 | 1.557 | 2.557 | 1.841 | 1.643 | 3.0 |
| 7) dIle:Lys ratio 0.83 | 3.097 | 1.514 | 2.518 | 1.948 | 1.665 | 1.5 |
| 8) Positive control (PC) | 3.119 | 1.541 | 2.472 | 1.862 | 1.605 | 1.5 |

SEM = 0.036 0.028 0.034 20.56 0.022 0.017

Regression analysis

| Contrast | SEM | Probabilities |
|----------|-----|---------------|
| Linear  | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| Quadratic | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |

R<sup>2</sup> linear = 0.598 0.650 0.427 0.938 0.657 0.007
R<sup>2</sup> quadratic = 0.668 0.733 0.510 0.962 0.732 0.002

1Values represent least-square means for 8 replicate pens with 25 chicks per pen at 42 d of age. Experiment 2.
2Treatments 1 to 7 are represented by analyzed digestible Ile to Lys ratios.
3Body weight gain.
4Feed intake.
5Determined using digestible Ile concentration of each treatment.
6Feed conversion ratio corrected for mortality.
7Calculated digestible Ile to Lys ratio = 0.70.
8Pooled standard error.

### Experiment 2

Positive linear and quadratic responses were observed ($P < 0.001$) for BW and BWG as dig Ile to Lys ratios increased in the diet for broilers with an approximate ending weight of 3.1 kg (Table 8). Similarly, FI and daily dig Ile intake displayed increasing linear and quadratic effects ($P < 0.001$) as dig Ile to Lys ratios were elevated from Trt 1 to 7. The FCR of broilers that consumed increasing dig Ile to Lys ratios were observed to decrease linearly and quadratically ($P < 0.001$). No effect ($P = 0.60$) of dietary dig Ile to Lys ratios was noted for
Dietary treatments

Response parameter Live Weight, kg of broilers (birds fed the PC and Trt 5 for the carcass characteristic of broilers from 30 to 42 d of age) (Table 9).

The contrast did not display any differences between fat weight as dietary dig Ile to Lys ratios were elevated, however, there was no effect on the fat yield observed. This result is in agreement with what was reported for broilers from 22 to 42 d of age, where dietary Ile concentration affected abdominal fat weight, but did not change yield (Mejia et al., 2011; Miranda et al., 2015). Birds fed Trt 5 had a reduced daily dig Ile intake compared with the broilers provided the PC diet; however, this was not caused by a reduction in FI. This may be due to Trt 5 containing a lower dig Ile concentration compared with the calculated values and was not similar in dig Ile with the PC diet. A numerical decrease was observed for the birds provided the PC diet compared with broilers consuming Trt 5 in FCR, and though it was not a significant effect there was an improvement of 6 point of FCR in the absence of blood cells.

Estimated optimum dig Ile to Lys ratios ranged from a 0.66 to 0.68 for BWG, FCR, BWM, and BMY. These estimates are congruent with previously reported optimum ratios that range from 0.66 to 0.69 for broilers from 1.0 to 3.0 kg BW (Baker, 1996; Mack et al., 1999; Miranda et al., 2015), though dietary Lys concentrations varied between studies. Mejia et al. (2011) reported higher optimum ratios of 0.69 for growth performance and 0.72 for BMY while utilizing a similar high producing broiler strain as the present study. Estimated optimum ratios were obtained utilizing linear broken-line regression analysis, as quadratic analysis did not produce a good fit with the response criteria (BWG SEM = 0.029 vs. 0.092). The treatment design was susceptible to being affected by lower analyzed ratios shifting data below the break point of the quadratic broken-line model, preventing a good fit. This was addressed in the experimental designs of Exp 1 and 3 with the addition of an 8th

Table 9. Carcass characteristics of male Yield Plus × Ross 708 broilers fed diets with increasing digestible Ile to Lys ratios from 1.6 to 3.1 kg BW (28 to 42 d of age).

| Dietary treatments | Carcass | Breast meat | Abdominal Fat |
|--------------------|---------|-------------|---------------|
|                     | Live Weight, kg | Weight, kg | Yield, % | Yield, kg | Weight, kg | Percentage, % |
| PC vs. Trt 5       | Linear   | Quadratic   | Linear   | Quadratic | Linear   | Quadratic   | SEM<sup>1</sup> | Coefficient of determination |
|                    | < 0.001  | < 0.001  | < 0.001  | < 0.001  | < 0.001  | < 0.001  | 0.005  | 0.52 |
| R<sup>2</sup> linear | 0.635   | 0.684   | 0.206   | 0.685   | 0.404   | 0.136   | 0.002  | 0.002 |
| R<sup>2</sup> quadratic | 0.716   | 0.771   | 0.237   | 0.789   | 0.494   | 0.153   | 0.012  | 0.012 |

<sup>1</sup>Values are least-square means of 8 replicate pens, with 14 birds being selected and processed at d 42. Experiment 2.

<sup>2</sup>Treatments 1 to 7 are represented by analyzed digestible Ile to Lys ratios.

<sup>3</sup>Calculated digestible Ile to Lys ratio = 0.70.

<sup>4</sup>Pooled standard error.

the incidence of mortality of broilers. The contrast displayed a difference between broilers consuming the PC and Trt 5 for daily dig Ile intake (P < 0.001), with the PC fed birds consuming 136 mg more dig Ile. In addition, there was a numerical decrease (P = 0.051) of 6 points in FCR for the PC birds relative to those on Trt 5.

Broilers fed increasing dig Ile to Lys ratios displayed positive linear and quadratic effects for carcass weight and yield (P < 0.001) (Table 9). Likewise, BWM and BMY responses of broilers increased linearly and quadratically (P < 0.001) as dig Ile to Lys ratio increased in the diet from 1.6 to 3.1 kg BW. There was no effect of increasing dig Ile to Lys ratios on abdominal fat yield (P = 0.52); however, positive linear and quadratic effects were observed (P = 0.003) for abdominal fat weight as dietary dig Ile to Lys ratios were elevated. The contrast did not display any differences between birds fed the PC and Trt 5 for the carcass characteristic of broilers (P > 0.05). Broilers fed progressive additions of dig Ile led to an optimum dig Ile to Lys ratio of 0.67 for BWG (P < 0.001) from 1.5 to 3.1 kg BW. Similarly, optimum dig Ile to Lys ratios were determined to be 0.67, 0.66, and 0.68 for FCR, BWM, and BMY, respectively, based on linear broken-line regression.

In agreement, Kidd et al. (2004) reported the total Ile requirement to range from 0.64 to 0.69% for growth performance and carcass characteristics from 30 to 42 d of age with a total Lys concentration of 1.05%. These authors also determined that optimum performance for broilers from 30 to 42 d of age could be obtained with a total daily Ile intake of 1,100 mg. This is considerably lower than the values of 1,600 to 1,650 mg/d of dig Ile obtained from broilers in the present research. This indicates that modern broiler strains may have a greater dietary need for Ile to optimize growth relative to genetic strains of the past. There was an increase of abdominal fat weight as dig Ile to Lys ratios were elevated, however, there was no effect on the fat yield observed. This result is in agreement with what was reported for broilers from 22 to 42 d of age, where dietary Ile concentration affected abdominal fat weight, but did not change yield (Mejia et al., 2011; Miranda et al., 2015). Birds fed Trt 5 had a reduced daily dig Ile intake compared with the broilers provided the PC diet; however, this was not caused by a reduction in FI. This may be due to Trt 5 containing a lower dig Ile concentration compared with the calculated values and was not similar in dig Ile with the PC diet. A numerical decrease was observed for the birds provided the PC diet compared with broilers consuming Trt 5 in FCR, and though it was not a significant effect there was an improvement of 6 point of FCR in the absence of blood cells.
titrated diet, allowing more data above the hypothesized optimum ratio. These data indicate an optimal dig Ile to Lys ratio of 0.66 to 0.68 is appropriate for broilers from 1.6 to 3.1 kg BW.

**Experiment 3**

Positive linear and quadratic effects were observed for BW and BWG ($P < 0.001$) of broilers as dig Ile to Lys ratios increased in the diet fed from 2.6 to 3.9 kg BW (Table 10). Similarly, dig Ile intake displayed linear and quadratic responses ($P < 0.001$), where values increased linearly and quadratically from Trt 1 to 8. For FI of broilers, quadratic responses were observed ($P < 0.001$), however, there was not a linear relationship between FI and dig Ile to Lys ratio ($P = 0.15$). Broilers that were fed progressive additions of dig Ile displayed decreasing linear and quadratic responses ($P < 0.001$) for FCR. There was no effect of increasing dig Ile to Lys ratios on the mortality of broilers. A difference was elucidated between birds provided the PC and Trt 5 for the daily dig Ile intake of broilers ($P < 0.001$), with the PC producing a larger dig Ile intake response. Blood cell inclusion had no effect on any other growth performance parameters of broilers evaluated from 2.6 to 3.9 kg BW ($P > 0.05$).

Broilers being fed increasing dig Ile to Lys ratios displayed linear and quadratic responses ($P < 0.001$) for carcass weight from 2.6 to 3.9 kg BW (Table 11). However, no effect of dig Ile to Lys ratios on carcass yield was observed ($P = 0.30$) as dig Ile increased in the diet. Positive linear and quadratic effects were observed ($P < 0.001$) for BMW and BMY of broilers when dietary Ile concentrations were increased. There was no effect of dig Ile to Lys ratios observed for abdominal fat weights ($P = 0.85$) or yields ($P = 0.12$). The contrast may have revealed an effect of blood cells inclusion for both carcass yield ($P = 0.016$) and BMY ($P = 0.017$) between broilers fed Trt 5 and the PC. No other differences were observed between these diets for carcass characteristics ($P > 0.05$). The optimum dig Ile to Lys ratio for BWG was determined at 0.63 ($P < 0.001$) utilizing linear broken-line regression from 2.6 to 3.9 kg BW (Table 6). Similarly, the optimum dig Ile to Lys ratio for FCR was determined as 0.69 ($P < 0.001$). The optimum dig Ile to Lys ratios for BMW and BMY were observed at 0.69 and 0.73 ($P < 0.001$), respectively, with linear broken-line analysis.

Kidd et al. (2004) reported the total Ile requirement of broilers from 42 to 56 d of age to range from 0.57 to 0.67% with a dietary Lys concentration of 0.90%. These authors reported daily total Ile intake necessary to obtain optimum performance of 1,154 mg, which agrees with the range of 1,100 to 1,200 mg/d that was obtained in the current study, though these are dig values. However, broilers from the previous study were grown with the range of 0.57 to 0.67% with a dietary Lys concentration of 0.90%. These authors reported daily total Ile intake necessary to obtain optimum performance of 1,154 mg, which agrees with the range of 1,100 to 1,200 mg/d that was obtained in the current study, though these are dig values. However, broilers from the previous study were grown with the range of 0.57 to 0.67% with a dietary Lys concentration of 0.90%. These authors reported daily total Ile intake necessary to obtain optimum performance of 1,154 mg, which agrees with the range of 1,100 to 1,200 mg/d that was obtained in the current study, though these are dig values. However, broilers from the previous study were grown with the range of 0.57 to 0.67% with a dietary Lys concentration of 0.90%. These authors reported daily total Ile intake necessary to obtain optimum performance of 1,154 mg, which agrees with the range of 1,100 to 1,200 mg/d that was obtained in the current study, though these are dig values. However, broilers from the previous study were grown with the range of 0.57 to 0.67% with a dietary Lys concentration of 0.90%. These authors reported daily total Ile intake necessary to obtain optimum performance of 1,154 mg, which agrees with the range of 1,100 to 1,200 mg/d that was obtained in the current study, though these are dig values. However, broilers from the previous study were grown with the range of 0.57 to 0.67% with a dietary Lys concentration of 0.90%.
having a lower dig Ile concentration than it was formulated to contain.

Optimum dig Ile to Lys ratios ranged from 0.69 to 0.73 for FCR, BMW, and BMY. Body weight gain produced an optimum ratio of 0.63, which is lower than previously reported ratios for this time period of 0.68 and 0.69 (Baker, 1996, 1997). The estimated optimum ratios for FCR and BMW were at 0.69, which is in agreement with previous reports for broilers grown to approximately 3.5 kg BW (Baker, 1997). The difference observed between responses of BWG and FCR have been observed previously for broilers of >3.0 kg (Kidd et al., 2000, 2004). These authors reported that the difference can be rationalized by increased FI responses to compensate for the limiting nutrient. Breast meat yield produced an optimum dig Ile to Lys ratio of 0.73, which is higher than previously published data (Corzo et al., 2002, 2008); however, it is in agreement with the dig Ile ratio obtained by Mejia et al. (2011) of 0.72 for broilers from 28 to 42 d of age. Based on these data, an optimal dig Ile to Lys ratio of 0.69 to 0.70 is appropriate for broilers from 2.5 to 3.9 kg BW.

### Statistical Models

Consideration must be given to the statistical model chosen to evaluate optimum dig AA ratios, as it can affect the results obtained. Broken-line regression analysis is commonly used as it provides a function that describes the responses to nutrient doses across all concentrations and provides a break point estimate of the optimum with an associated standard error (Robbins et al., 2006). However, the type of broken-line model fit to a given data set can change the output of the analysis based on the shape of the data. Linear broken-line regression presumes that the responses to a nutrient dose are linear, when in most cases of dose response designs responses are curvilinear in nature (Robbins et al., 2006). In these cases, linear broken-line analysis can still provide a satisfactory fit to the data; however, this model can underestimate a requirement compared to a quadratic model that achieves a significant fit. The issue that is observed with quadratic broken-line models is that a minimum of 3, and preferably 4, data points are required above the break point of the model for it to accurately predict an optimum requirement (Robbins et al., 2006). These authors reported that problems can also be observed if there are large variations in the responses of broilers above a hypothesized optimum that affect the shape of the plateau. Many of these issues occurred in the present research, and likely affected the ability of the quadratic broken-line model to accurately predict the optimum dig Ile to Lys ratios of broilers. Additionally, Ile concentrations being analyzed lower than formulated values may have contributed to a linear broken-line model better fitting the data in many cases. The lower values shifted the data points down so that there were insufficient data above the break point for a quadratic model to estimate the optimums. Based on the responses observed, both linear and quadratic broken-line analysis provided accurate estimates of dig Ile ratios from 1.0 to 4.0 kg BW dependent upon the trial and variable (Table 7).

### Response Criteria

In the current research, optimum dig Ile to Lys ratios varied based on the response criteria. Optimum dig Ile

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**Table 11.** Carcass characteristics of male Yield Plus × Ross 708 broilers fed diets with increasing digestible Ile to Lys ratios from 2.6 to 3.9 kg BW (35 to 49 d of age).1

| Response parameter | Live Weight, kg | Weight, % | Yield, % | Breast meat | Weight, % | Abdominal fat | Percentage, % |
|--------------------|----------------|----------|---------|-------------|----------|--------------|---------------|
| **Response Criteria** |                |          |         |             |          |              |               |
| **Carcass**        |                |          |         |             |          |              |               |
| **Dietary treatments** |                |          |         |             |          |              |               |
| 1) dIle:Lys ratio 0.45 | 3.678         | 2.801    | 76.28   | 0.987       | 26.82    | 0.034        | 0.92           |
| 2) dIle:Lys ratio 0.53 | 3.777         | 2.879    | 76.25   | 1.017       | 26.95    | 0.037        | 0.97           |
| 3) dIle:Lys ratio 0.56 | 3.937         | 3.014    | 76.53   | 1.075       | 27.28    | 0.035        | 0.88           |
| 4) dIle:Lys ratio 0.60 | 3.950         | 3.008    | 76.15   | 1.076       | 27.24    | 0.035        | 0.89           |
| 5) dIle:Lys ratio 0.66 | 3.967         | 3.031    | 76.37   | 1.086       | 27.39    | 0.033        | 0.82           |
| 6) dIle:Lys ratio 0.70 | 4.026         | 3.085    | 76.71   | 1.122       | 27.81    | 0.032        | 0.81           |
| 7) dIle:Lys ratio 0.72 | 4.045         | 3.101    | 76.84   | 1.120       | 27.72    | 0.034        | 0.85           |
| 8) dIle:Lys ratio 0.74 | 3.991         | 3.050    | 76.46   | 1.108       | 27.77    | 0.036        | 0.90           |
| 9) Positive control (PC)3 | 3.970         | 3.065    | 77.29   | 1.113       | 28.10    | 0.033        | 0.52           |
| **SEM4** | 0.038          | 0.030    | 0.27    | 0.014       | 0.22     | 0.002        | 0.05           |
| **Regression analysis** |                |          |         |             |          |              |               |
| **Linear** |                |          |         |             |          |              |               |
| Coef | <0.001         | <0.001   | 0.12    | <0.001     | <0.001   | 0.85         | 0.12           |
| **Quadratic** |                |          |         |             |          |              |               |
| Coef | <0.001         | <0.001   | 0.30    | <0.001     | <0.001   | 0.82         | 0.12           |
| **Contrast** |                |          |         |             |          |              |               |
| PC vs. Trt 5 | 0.95          | 0.42     | 0.016   | 0.13        | 0.017    | 0.98         | 0.99           |
| **R² linear** | 0.447         | 0.447    | 0.037   | 0.507       | 0.283    | 0.001        | 0.039          |
| **R² quadratic** | 0.567         | 0.560    | 0.039   | 0.584       | 0.288    | 0.007        | 0.066          |

1Values are least-square means of 8 replicate pens, with 14 birds being selected and processed at d 50. Experiment 3.

2Treatments 1 to 8 are represented by analyzed digestible Ile to Lys ratios.

3Calculated digestible Ile to Lys Ratio = 0.68.

4Pooled standard error.
to Lys ratios are more pronounced with breast meat yield compared with growth performance (Kidd et al., 2004; Mejia et al., 2011; Miranda et al., 2015). This response was observed for Exp 2 and 3, with optimum ratios for BMY being 3 to 5 points greater than growth performance characteristics. Experiment 1 produced a higher optimum ratio for BW relative to other parameters, including BMY. Corzo et al. (2002) reported that Ile needs of broilers heavier than 3.0 kg are greater for breast tissue development relative to other growth. However, similar responses have been reported for broilers from 1.5 to 2.5 kg as well (Kidd et al., 2004). This is critical, especially if final market weights larger than 3.0 kg are being targeted. Feeding higher dig Ile to Lys ratios through the grower and finisher periods may help to optimize breast meat yields.

In conclusion, data from these 3 experiments indicated that the optimum dig Ile to Lys ratios for growth performance are largely in agreement with previous research. However, the Ile intake required to optimized growth and feed efficiency may be greater in modern broiler strains relative to those of the past. Estimated optimums for BMY in the current studies are greater than previously reported for broilers and may also warrant increased Ile intake. Corn and soybean meal-based diets formulated with a dig Ile to Lys ratio of 0.67 to 0.69 will be adequate for broilers to obtain optimum growth performance and optimum meat yield responses from 1.0 to 4.0 kg BW.

DISCLOSURES

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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