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# Prediction of net energy of feeds for broiler chickens

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ABSTRACT

Net energy (NE) enables the prediction of more accurate feed energy values by taking into account the heat increment which is approximately 25% of apparent metabolizable energy (AME) in poultry. Nevertheless, application of NE in poultry industry has not been practiced widely. To predict the NE values of broiler diets, 23 diets were prepared by using 13 major ingredients (wheat, corn, paddy rice, broken rice, cassava pellets, full-fat soybean, soybean meal, canola meal, animal protein, rice bran, wheat bran, palm kernel meal and palm kernel oil). The diets were formulated in order to meet the birds' requirements and get a wide range of chemical compositions (on DM basis; 33.6% to 55.3% for starch; 20.8% to 28.4% for CP, 2.7% to 10.6% for ether extract [EE] and 7.0% to 17.2% for NDF), with low correlations between these nutrients and low correlations between the inclusion levels of ingredients allowing for the calculation of robust prediction equations of energy values of diets or ingredients. These diets were fed to Ross 308 broilers raised in 12 open-circuit respiratory chambers from 18 to 23 d of age (4 birds per cage) and growth performance, diet AME content and heat production were measured, and dietary NE values were calculated. The trial was conducted on a weekly basis with 12 diets measured each week (1 per chamber), 1 of the 23 diets (reference diet) being measured each week. Each diet was tested at least 8 times. In total, 235 energy balance data values were available for the final calculations. Growth performance, AME (15.3 MJ/kg DM on average) and AME/GE (79.4% on average) values were as expected. The NE/AME value averaged 76.6% and was negatively influenced by CP and NDF and positively by EE in connection with efficiencies of AME provided by CP, EE and starch for NE of 73%, 87% and 81%, respectively. The best prediction equation was: NE = (0.815 × AME) − (0.026 × CP) + (0.020 × EE) − (0.024 × NDF) with NE and AME as MJ/kg DM, and CP, EE and NDF as % of DM. The NE prediction equations from this study agree with other recently reported equations in poultry and are suitable for both ingredients and complete feeds.


## 1. Introduction

Energy represents the major cost in broiler chicken production and hence it is of great importance to determine both the energy requirement of the birds precisely and the energy value of feeds to meet this requirement. Moreover, difficulty in finding alternative sources of raw ingredients for animal feeds has been increasing with the growing sustainability concerns and geo-political issues. In poultry, apparent metabolizable energy (AME) and AME corrected to zero nitrogen retention (AMEn) are the mostly widely used concepts to express bird energy requirements and feed energy values in poultry production. Nevertheless, it is claimed that up to 70% of nitrogen (N) consumed by poultry is retained in the body

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and AME standardized (AMEs) for a representative proportion of N intake that is retained in the body or exported in eggs has been proposed as a more representative approach (Barzegar et al., 2019; Cozannet et al., 2010). Furthermore, approximately 25% of AME is eliminated as heat during nutrient metabolism in broilers and that percentage is variable between nutrients and then between feedstuffs (Carré et al., 2014; Choct, 1999; Wu et al., 2019). This clearly highlights the inadequacy of an AME system to accurately predict the energy value of feeds for poultry. The net energy (NE) system has been widely regarded as a more accurate concept to predict the energy requirements of animals and the energy value of feeds (Carré et al., 2014; De Groote, 1974; Noblet et al., 2023a; Van der Klis and Kwakernaak, 2008). Therefore, compared to digestible energy (DE) or metabolizable energy (ME), NE predicts growth performance more accurately, at least in pigs (Noblet et al., 2023a).

Unlike in pigs and ruminant species, and despite some recent proposals for predicting NE in poultry feeds (Barzegar et al., 2019; Carré et al., 2014; Wu et al., 2019), NE in poultry has not been widely implemented due to limited scientific and validation studies. However, the advantages of NE over AME have been studied for decades. De Groote (1974) compared NE and AME based broiler diets and concluded that NE based broiler diets were economically more effective. It has been reported that the NE system predicted the growth performance of broilers more accurately than the ME system did, especially in the grower stage (Zou et al., 2021). This study aimed to complement the recent studies of Carré et al. (2014) and Wu et al. (2019) conducted each on a limited number of diets and with specific methodologies in order to propose additional NE prediction equations for broilers.

## 2. Materials and methods

### 2.1. Animal ethics

This study was reviewed and approved by the Institutional Animal Care and Use Committee of the Feed Research and Innovation Center, Charoen Pokphand Foods. All the procedures that involved animals were conducted in accordance with farming practices and ethical guidelines outlined in RSPCA welfare standards for meat chickens (RSPCA, 2017).

### 2.2. Housing

The study was conducted in a closed house (22 m × 5.6 m × 3 m in length, width, and height, respectively) where ambient temperature, air pressure and ventilation were controlled by a positive pressure air conditioning system (Natural Green Innovation, Thailand). The temperature inside the house was adjusted to approximately 23 °C. Additionally, dehumidifiers were installed to prevent moisture condensation inside the respiratory chambers. Custom made transparent polycarbonate chambers were placed inside the house and all the birds were raised inside those chambers.

All chambers measured 60 cm, 50 cm and 55 cm in length, width and height, respectively (165 L in volume), and were equipped with stainless steel mesh floors, excreta collection trays, feeders, drinking water nipples and air inlets. There were 48 adaptation chambers and 12 respiratory chambers. Adaptation chambers were designed to acclimatize the birds from 1 to 17 d of age and equipped with a 100 W ceramic infrared heating lamp and an exhaust fan in each chamber.

Only the respiratory chambers were connected with the Oxymax open circuit indirect calorimetry system (Columbus Instruments, Ohio, U.S.A) to measure $O_2$ and $CO_2$ exchanges in each chamber. Birds were kept inside the respiratory chambers from 18 to 23 d of age. A partition divided the adaptation and respiratory chambers. The compartment that housed the respiratory chambers was designed to isolate the birds from outside interference such as loud noise or presence of humans in sight in order to maintain the birds' activity at a normal level. Another partition was used to divide the station gas sensors, samplers, computers, and calibration gas cylinders. Each chamber had 4 air inlets of 0.5 cm diameter at the base and the lids were sealed with rubber lines and clamps to avoid air leaks.

Ambient temperature was set to gradually reduce from 36 to 25 °C during the first 14 d of age, and remained at 25 °C until 23 d of age. Likewise, daily lighting duration was gradually reduced from 24 to 16 h during the first 14 d and was maintained at 16 h of lighting from 15 d onwards. Light-off hours always started from 22:00. Temperature and humidity inside each respiratory chamber were recorded at 10 min intervals using iButton data loggers (DS1923, Thermochron, NSW, Australia).

### 2.3. Preliminary trial

A preliminary trial was conducted to evaluate the effect of the 23 experimental diets on growth performance characteristics of the birds. The objective was to confirm that all diets supported normal growth and feeding behavior of the birds in order to obtain NE values of diets under rather high and comparable levels of performance (Noblet et al., 2022). A total of 184 Ross 308 male day-old chicks were allocated into 46 conditioning chambers with 4 birds per chamber. Birds were randomly assigned to the 23 dietary treatments (2 replicates per treatment). A reference starter phase diet was given from 0 to 14 d and test diets were given between 15 and 23 d. Body weight gain and feed intake (FI) of the birds between 15 and 23 d as well as chemical and physical characteristics of the diets were measured.

### 2.4. Diets

All the diets in this study met the minimum nutrient requirements set by the breeding company (Aviagen, 2019) and were provided ad libitum. A single starter diet was prepared for 0 to 14 d of age followed by 23 test diets for 15 to 22 d of age. The starter diet was based on corn, cassava, broken rice, wheat, full fat soybean, animal protein, soybean meal, canola, rice bran, wheat bran, palm kernel meal and palm kernel oil. The calculated composition (DM basis) was 13.9 MJ/kg AME, 24% crude protein (CP), 9% ether extract (EE) and 4.5% crude fiber (CF). The diet was pelleted and then crumbled.

The 23 pelleted test diets of the study fall into 4 categories based on their composition: 1 reference diet, 5 starch diets, 6 CP diets, 4 fat (oil) diets and 7 other diets. The reference diet was formulated with 13 major raw ingredients by maintaining the normal levels of nutrient composition while starch diets were prepared by varying the levels of starch-rich ingredients and CP diets and fat (oil) diets were prepared by varying the inclusion levels of protein rich ingredients and fat (oil) ingredients, respectively. The 7 other diets aimed to minimize the correlations between dietary chemical constituents (CP, fat, starch, dietary fiber [DF]) of the test diets by varying the levels of raw ingredients. Levels of essential amino acids together with Ca, P and vitamins were adjusted to meet the requirements of the birds. All diets were supplemented with phytase and NSPase enzymes as in routine practice. As stated above, the study also intended to evaluate the ingredients used in the diets for their AME and NE values in broilers. In addition to the constraints of low correlation between chemical constituents, the levels of ingredients were also adjusted in order to minimize the correlations between all levels of ingredients. That allowed the prediction of AME and NE values of ingredients according to the multiple regression approach (Noblet et al., 2022). A summary of raw ingredients levels in the diets and the analyzed chemical values of diets are presented in Tables 1 and 4, respectively. The correlations between some chemical constituents and energy values are presented in Table 2.

Diets were prepared by including major raw ingredients that are commonly used in the industry and those with potential future use (rice products, for instance) in poultry. The chemical composition of each ingredient was checked by Near Infrared methods before and after the grinding process. Selected raw ingredients were stored at 10 °C in the warehouse. All diets were prepared in 2 d; a crumble diet was prepared for the starter phase and pelleted diets were prepared for the grower experimental phase. All diets were packed into 10-kg bags and transported to the farm. In order to store the feeds for long term use, all the bags were vacuum sealed and stored inside a cold room at 4 °C. Throughout the storage period, moisture and major chemical composition including CP, EE, starch, fat and fiber components were analyzed every 3 months.

### 2.5. Birds and trial organization

A total of 2520 Ross 308 (Aviagen, U.S.A) male broiler chicks from the FRIC1 hatchery (CPF, Chonburi, Thailand) were used in the current study. There were 3 phases in the trial: starter phase (0–12 d), transition phase (13–17 d) and evaluation phase (18–23 d). During the first two phases, birds were raised inside the adaptation chambers that resembled the respiratory chambers to acclimatize to the evaluation-like environment. A single reference diet was fed to all birds throughout the starter phase. The transition phase was designed to replace the starter diet with respective test diets (25%, 50% and 75%) over 3 consecutive days followed by 100% test diets. During the starter and transition phases, 10 birds per chamber were raised. On 18 d of age, 4 birds per chamber were selected based on their mean bodyweight and moved into respiratory chambers where they were fed and maintained for 5 d.

For each series, 2 sets of 6 respiratory chambers totaling 12 chambers were run at the same time. The reference diet was included in every series as a control. To complete one replicate of 23 diets, the reference diet and 11 other diets were run for 1 week and the remaining 11 diets plus the reference diet were run the following week. In other words, it took 2 consecutive weeks to complete 1 replicate of 23 diets generating 2 observations for the reference diet and 1 observation for the other 22 diets. For each diet (except the reference diet), a minimum of 8 replicates per diet was run and it was arranged not to repeat the measurements on one diet in the same chamber. The total trial duration was approximately 6 months for the measurements in the respiration chambers. In the end, a total of 252 observations were available; however, 17 of them were excluded due to equipment or animal reasons, resulting in 235 available observations for the statistical analyses.

**Table 1**
Ingredient composition of test diets (g DM/kg DM).

| Ingredients | Test diets ($n$ = 23) | | | |
|---|---|---|---|---|
| | No. of diets[1] | Mean | Min. | Max. |
| Corn | 16 | 178 | 0 | 392 |
| Cassava pellet | 14 | 51 | 0 | 197 |
| Broken rice | 15 | 135 | 0 | 402 |
| Paddy rice | 13 | 68 | 0 | 243 |
| Wheat | 20 | 109 | 0 | 451 |
| Animal protein | 15 | 30 | 0 | 79 |
| Full fat soybean | 11 | 25 | 0 | 82 |
| Soybean meal | 23 | 225 | 92 | 336 |
| Canola meal | 14 | 35 | 0 | 123 |
| Rice bran | 12 | 27 | 0 | 152 |
| Wheat bran | 9 | 21 | 0 | 148 |
| Palm kernel meal | 11 | 22 | 0 | 100 |
| Palm kernel oil | 19 | 39 | 0 | 89 |
| DL-Methionine (99%) | 23 | 4.0 | 2.3 | 5.6 |
| L-Lysine-HCl (78%) | 21 | 3.6 | 0.0 | 7.6 |
| L-Threonine (98.5%) | 22 | 2.0 | 0.0 | 3.8 |
| Monocalcium phosphate | 15 | 4.4 | 0.0 | 13.2 |
| Limestone | 21 | 7.4 | 0.0 | 14.2 |
| Salt | 23 | 3.6 | 3.1 | 4.4 |
| Sodium bicarbonate | 23 | 1.1 | 1.1 | 1.1 |
| Choline | 9 | 0.4 | 0.0 | 1.6 |
| NSP enzyme[2] | 23 | 0.1 | 0.1 | 0.1 |
| Phytase[3] | 23 | 0.1 | 0.1 | 0.1 |
| Other amino acids[4] | 15 | 6.2 | 0.0 | 20.8 |
| Trace minerals and vitamins premix[5] | 23 | 3.6 | 3.5 | 3.6 |

NSP = nonstarch polysaccharides.
[1] Number of diets where the ingredient was used.
[2] Rovabio advance T-flex (contained endo-1,4-xylanase [6250 visco unit/g], and endo-1,3(4)-glucanase [4300 visco unit/g]).
[3] Ronozyme HiPhos (GT) (1000 FYT/g).
[4] Contained glycine, tryptophan, valine, arginine, leucine and isoleucine in 15, 12, 15, 10, 6 and 15 diets, respectively.
[5] Contained vitamins A, $D_3$, E and K, thiamin, riboflavin, Cu, Fe, Mn, Se and Zn.

### 2.6. Respiratory chamber measurements

Each of the 12 respiratory chambers was connected to a 40 L/min pump and a control box that controlled air flowrate and sampled air inside the chamber. Sampled air was channeled to the $O_2$ and $CO_2$ sensors through an ammonia trap and air-drying unit attached to drying columns filled with calcium sulphate granules (Drierite, California, U.S.A). The air inside the respiratory chamber was continuously sampled over 90 s intervals per chamber with 60 s for settling and 30 s for measuring. For each 6 chambers set, it thus took 630 s, including one reference (or ingoing) air, to complete one round of measurements for each set of 6 chambers. The system used paramagnetic $O_2$ sensors with a 0% to 40% detection range and resolution of 0.0001%. The detection range and resolution for infrared $CO_2$ sensors were 0% to 1% and 0.0001%, respectively. During daily respiration measurements, $O_2$ and $CO_2$ sensors were calibrated every morning using a reference gas and pure nitrogen gas, at which time feed was added. Calibration and feeding took approximately 1 h and daily gaseous exchange data were recorded for approximately 23 h.

Live body weight (BW) and feed weight were recorded on 18 and 23 d of age. For each diet, DM content was measured each week in order to calculate feed DM intake while in the respiration chambers. Excreta were collected and weighed on 23 d of age following 8 h of feed withdrawal starting at 8:00. Fresh excreta were carefully cleared from spilled feed and feathers before weighing. The spilled feeds were weighed and included in FI calculations. Excreta inside each tray were thoroughly mixed and a 200 g sub-sample was collected to determine excreta DM at 108 °C for 18 h. Another portion of 800 g fresh excreta was weighed and dried at 60 °C for 72 h or until no weight change was observed. Upon drying, those samples were ground and stored inside the desiccator cabinet for further lab analyses.

### 2.7. Analysis of feeds and excreta

Feeds were sampled every 3 months and analyzed for gross energy (GE), N, EE, starch, CF, acid detergent fiber (ADF), neutral detergent fiber (NDF), ash, Ca and P at the CPF Central laboratory (Bangna, Bangkok, Thailand). Ground excreta samples were analyzed for GE, N, Ca and P contents. At the time of chemical analysis, DM was also measured to express chemical composition of feeds and excreta on a DM basis. The GE of feed and excreta were

**Table 2**
Correlations between nutrient parameters of the 23 diets used for the prediction of AME and NE values.

| Nutrients | CP | EE | Starch | CF | ADF | NDF | FI | GE | AME | NE | AME/GE | NE/AME |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CP | | | | | | | | | | | | |
| EE | −0.29 | | | | | | | | | | | |
| Starch | −0.45* | −0.40 | | | | | | | | | | |
| CF | −0.06 | 0.03 | −0.62** | | | | | | | | | |
| ADF | 0.02 | 0.01 | −0.67*** | 0.96*** | | | | | | | | |
| NDF | −0.09 | 0.03 | −0.60** | 0.89*** | 0.93*** | | | | | | | |
| FI | 0.04 | −0.67*** | −0.12 | 0.61** | 0.64*** | 0.63** | | | | | | |
| GE | −0.05 | 0.94*** | −0.50* | 0.01 | 0.04 | 0.08 | −0.68*** | | | | | |
| AME | −0.30 | 0.71*** | 0.25 | −0.59** | −0.61** | −0.57** | −0.91*** | 0.67*** | | | | |
| NE | −0.35 | 0.70*** | 0.28 | −0.57** | −0.61** | −0.56** | −0.90*** | 0.64*** | 0.99*** | | | |
| AME/GE | −0.37 | 0.22 | 0.71*** | −0.78*** | −0.84*** | −0.82*** | −0.69*** | 0.12 | 0.82*** | 0.83*** | | |
| NE/AME | −0.52* | 0.60** | 0.37 | −0.44* | −0.52* | −0.48* | −0.74*** | 0.49* | 0.88*** | 0.92*** | 0.79*** | |
| RQ | −0.40 | −0.64** | 0.93*** | −0.41 | −0.46* | −0.42* | 0.22 | −0.75*** | −0.08 | −0.04 | 0.48* | 0.11 |

ADF = acid detergent fiber; AME = apparent metabolizable energy; CF = crude fiber; CP = crude protein; EE = ether extract (or fat); FI = feed intake (gram DM per kilogram $BW^{0.70}$ per day); GE = gross energy; NDF = neutral detergent fiber; NE = net energy; RQ = respiratory quotient.
Numbers with asterisks were significantly different from zero; $*P < 0.05$, $**P < 0.01$ and $***P < 0.001$.

analyzed by a LECO bomb calorimeter (LECO, USA) based on ISO 9831 (ISO, 2008). Nitrogen, ash, Ca and P analysis of feed and excreta were based on ISO 16634-1 (ISO, 2008), ISO 5984 (ISO, 2002), ISO 15510 (ISO, 2007) and ISO 15510 (ISO, 2007), respectively. For feed samples, analysis for EE and CF were based on AOCS procedures (AOCS, 2017) and analysis for starch was based on polarimetric starch analysis of ISO 6493 (ISO, 2000). Analysis of ADF and NDF were based on the filter bags system developed by Ankom Technology where acid detergent solution was used for ADF analysis and alpha-amylase and neutral detergent solution were used for NDF analysis (Ankom, Tech. Co., Fairport, NY, USA).

### 2.8. Calculation of growth performance and energy values

Body weights of the birds were measured individually and only the mean per chamber was used in the calculations. Feed intake, FCR and energy values of diets were expressed on DM basis while the energy utilization values were expressed as a percentage. Energy balance for the birds was calculated per day and per bird and also per kilogram metabolic body weight ($BW^{0.70}$) according to Noblet et al. (2015).

Growth performance of birds was calculated according to usual methods. Nitrogen balance data, expressed per bird per day and % of N intake, were calculated as follows:

$$\text{N intake (g/bird per day)} = \text{FI} \times \text{N in feed (\%)}/100,$$

$$\text{N excreted (g/bird per day)} = \text{Excreta weight} \times \text{N in excreta (\%)}/100,$$

$$\text{N retained (g/bird per day)} = \text{N intake} - \text{N excreted},$$

$$\text{N retained (\%)} = \text{N retained (g)} \times 100/\text{N intake (g)}.$$

For the calculation of energy balance components, heat production (HP) was calculated according to the equation of Brouwer (1965) but expired methane and urinary N values were not accounted for calculation. The equation used $O_2$ and $CO_2$ exchanges to predict HP as follows:

$$\text{HP (kJ)} = [16.18 \times O_2 \text{ consumed (L)}] + [5.02 \times CO_2 \text{ exhaled (L)}].$$

Heat increment (HI) was determined by subtracting fasting heat production (FHP) from HP. Fasting heat production values of 450 kJ per kilogram $BW^{0.70}$ were adopted (Noblet et al., 2015). The respiratory quotient (RQ) values were obtained by dividing the volume of $CO_2$ exhaled by the volume of $O_2$ inhaled.

To measure AME, the total collection method described by Bourdillon et al. (1990) with slight modifications was used. Zero nitrogen correction AME was achieved by using 34.4 kJ/g of retained N as the correction coefficient. An AMEs value was also calculated by assuming that 60% of N intake is retained in the body, with that proportion being representative of modern broilers nutritional conditions (Barzegar et al., 2019; Cozannet et al., 2010; Wu et al., 2019). Net energy was calculated by subtracting HI from AME. Calculation of AME, AMEn, AMEs and NE were as follows and expressed as MJ per kilogram feed DM:

$$\text{AME (MJ/kg)} = (GE_{intake} - GE_{excreta})/\text{FI},$$

$$\text{AMEn (MJ/kg)} = \text{AME} - [\text{N retained (g/kg feed DM)} \times 34.4],$$

$$\text{AMEs (MJ/kg)} = \text{AMEn} + [\text{N in feed (\%DM)} \times 34.4 \times 0.60],$$

$$\text{NE (MJ/kg)} = (\text{AME} - \text{HI})/\text{FI}.$$

Finally, the quantities of retained energy (RE) and its partition between protein and fat were calculated as follows:

$$\text{RE} = \text{AME} - \text{HP},$$

$$RE_{protein} = \text{N retained (g)} \times 6.25 \times 23.6,$$

$$RE_{fat} = \text{RE} - RE_{protein},$$

where 23.6 represented the energy value of protein gain (kJ/g) (Larbier and Leclercq, 1994).

### 2.9. Statistical analyses

JASP version 0.17.1 (University of Amsterdam, The Netherlands) was used to perform the following analyses. First, all selected observations ($n = 235$) were subjected to a two-way analysis of variance (ANOVA) with the effects of diet and replicate in order to characterize the diet effect and the residual variability of the measurements estimated from the residual standard deviation (RSD) of the model. Second, mean values per diet were calculated from all available observations of one diet to harmonize the importance of each diet in the 23 diets dataset in the further statistical analyses. For the 23 diets, correlation coefficients between chemical constituents and energy values or energy efficiencies were calculated. A first set of linear multiple regressions with no intercept was established in order to quantify the energy contributions as GE, AME and NE of the major nutrients (CP, EE, starch, NDF and Residue1, on one hand, and CP, EE, starch and Residue2, on the other hand); Residue1 is the difference between OM and the sum of CP, starch, EE and NDF and Residue2 is the difference between OM and the sum of CP, starch and EE. A second set of stepwise linear regression equations with intercept values was generated to determine the impact of chemical constituents on energy utilization (AME/GE, NE/AME). In the last set of equations, a stepwise linear regression method was also used to predict AME from chemical constituents and NE from AME and chemical constituents. The RSD values were used to highlight the precision of the prediction models.

## 3. Results

### 3.1. Preliminary trial and diet composition

The minimum to maximum values of final BW, BW gain and FI of the birds during 15 to 23 d of age of the preliminary trial ranged from 1241 to 1405 g, 749 to 903 g and 982 to 1136 g, respectively. These values exceeded the broiler growth performance objectives recommended for Ross 308, which confirmed that none of the diets had negative effect on growth performance. Physical characteristics (pellet durability index, hardness, and screen size) of the diets were found to conform to the standard guidelines.

Chemical analysis values of the diet samples over the preliminary trial and the main trial were in agreement with the diet formulation objectives for each diet and therefore quite variable between diets (Table 4); our experimental diets were then representative of all practical dietary situations. The correlations between major nutrients (Table 2), especially between CP and EE, were also as expected.

### 3.2. Growth performance and energy values

Growth performance and energy balance of the birds, energy values and energy utilization values of the feeds, are presented in Tables 3 and 4. The trial lasted more than 6 months. Even though the birds were supplied continuously from the same hatchery, differences in “bird” quality were inevitable. Most criteria were then affected by replicate in connection with differences in initial BW and/or feeding behavior and/or bird “quality” between the successive replicates. In order to simplify the presentation, only the diet effect was presented.

Body weight gain, FI and FCR were significantly different among the treatments. Likewise, significant effects of diets on energy intakes and energy cost of BW gain were also observed. There were significant differences among the treatments for both N intake and retention. Predictably, a strong negative relationship between N retention coefficient (%) and dietary CP content was observed, the lowest value (65%) being observed with the high CP diets and the highest (75%) with the low CP diets.

There was a good agreement between energy intakes (AME and NE) per day and per kilogram $BW^{0.70}$ and all values were significantly affected by diet composition; the lowest energy intakes (1.62 MJ AME/kg $BW^{0.70}$) were observed with the high CP diets and the highest energy intakes (1.73 MJ AME/kg $BW^{0.70}$) with the low CP and/or high fat diets. On the other hand, no significant differences among diets for HP and HI were observed and approximately 50% of AME intake was dissipated as HP. In accordance with changes in energy intakes between diets and the absence of significant effect of diet on HP, total RE and its partition between protein and fat were affected by diet composition and especially their CP content, on one hand and dietary fat content, on the other hand. Respiratory quotient values, as expected, were correlated with dietary EE and starch content (Table 2); the lowest values (<0.95) being observed in the high fat diets and the highest values (>1.02) in the high starch/low fat diets. As with important differences in dietary fat and fiber contents, energy values of feeds and energy utilization values were significantly affected by dietary treatment.

Logically, the AME and NE values were positively correlated with EE and negatively with the DF indicators (CF, ADF or NDF; Table 2). On average, broilers utilized 79.4% of dietary GE as AME with a range between 74.8% and 84.7% (Table 4). The variation of this metabolizability ratio is mainly dependent on the DF content (Table 2); the lowest values being observed with the high CF, ADF or

**Table 3**
Effect of diet composition on growth performance, energy balance, energy values and energy utilization of diets in broiler chickens ($n = 235$ observations; duration: 5 d)[1].

| Item | Mean | Min. | Max. | RSD | *P*-value (diet) |
|---|---|---|---|---|---|
| Growth performance | | | | | |
| Initial BW, g | 686 | 613 | 756 | 21 | 0.980 |
| FI, g DM/d | 103 | 89 | 125 | 4 | <0.001 |
| BW gain, g/d | 89 | 72 | 108 | 5 | <0.001 |
| FCR, g DM/g | 1.16 | 0.99 | 1.29 | 0.03 | <0.001 |
| AME intake, kJ/d | 1574 | 1380 | 1793 | 67 | <0.001 |
| NE intake, kJ/d[2] | 1206 | 1018 | 1439 | 62 | <0.001 |
| AME/BW gain, kJ/g | 17.7 | 15.5 | 20.0 | 0.5 | <0.001 |
| NE/BW gain, kJ/g | 13.6 | 11.6 | 16.2 | 0.5 | <0.001 |
| Nitrogen balance, g/d | | | | | |
| Intake | 4.0 | 3.1 | 5.1 | 0.2 | <0.001 |
| Retained | 2.9 | 2.3 | 4.1 | 0.2 | <0.001 |
| Retained, % of intake | 73.1 | 62.1 | 80.7 | 2.5 | <0.001 |
| Energy balance, kJ/kg $BW^{0.70}$ per day | | | | | |
| FI, g DM/kg $BW^{0.70}$ per day | 110 | 97 | 124 | 4 | <0.001 |
| AME intake | 1685 | 1509 | 1861 | 59 | <0.001 |
| HP | 842 | 759 | 939 | 34 | 0.252 |
| RE | | | | | |
| Total | 843 | 681 | 1046 | 59 | <0.001 |
| As protein | 457 | 358 | 616 | 21 | <0.001 |
| As fat | 386 | 169 | 596 | 47 | <0.001 |
| HI[3] | 394 | 311 | 492 | 34 | 0.252 |
| NE intake | 1291 | 1129 | 1494 | 59 | <0.001 |
| Protein/fat ratio in RE | 1.26 | 0.63 | 3.02 | 0.18 | <0.001 |
| Respiratory quotient | 0.987 | 0.895 | 1.103 | 0.025 | <0.001 |
| Energy values, MJ/kg DM | | | | | |
| AME | 15.28 | 13.74 | 17.06 | 0.23 | <0.001 |
| AMEn | 14.31 | 12.76 | 15.95 | 0.21 | <0.001 |
| AMEs | 15.11 | 13.67 | 16.84 | 0.21 | <0.001 |
| NE | 11.71 | 9.99 | 13.69 | 0.37 | <0.001 |
| Energy utilization, % | | | | | |
| AME/GE | 79.4 | 73.4 | 86.7 | 1.2 | <0.001 |
| AMEn/GE | 74.4 | 68.0 | 81.4 | 1.1 | <0.001 |
| AMEs/GE | 78.5 | 72.7 | 85.3 | 1.1 | <0.001 |
| NE/AME | 76.6 | 70.6 | 81.9 | 1.9 | <0.001 |
| NE/AMEn | 81.8 | 75.2 | 86.9 | 2.1 | 0.022 |
| NE/AMEs | 77.4 | 71.1 | 82.8 | 2.0 | <0.001 |

AME = apparent metabolizable energy; AMEn = AME corrected for zero nitrogen retention in the body; AMEs = AME standardized (corrected with nitrogen retained in the body equal to 60% of nitrogen intake); BW = body weight; DM = dry matter; FCR = feed conversion ratio; FI = feed intake; GE = gross energy; HI = heat increment; HP = heat production; NE = net energy; RE = retained energy; RSD = residual standard deviation.
Respiratory quotient: $CO_2/O_2$; $BW^{0.70}$: metabolic BW (kg) as mean of daily metabolic BW values over 5 d.
[1] Mean and range of individual data ($n = 235$) obtained for 23 diets (19 observations for the reference diet and 7 to 11 observations per diet for the other diets); each observation corresponds to the measurements conducted on a group of 4 broilers over 5 consecutive days; data on performance, nitrogen balance and energy balance are expressed per bird. The RSD is from a two-way analysis of variance including diet and replicate effects; replicate effect was significant for most criteria; only the level of diet effect is indicated.
[2] NE was estimated by subtracting HI from AME (see text).
[3] HI was calculated by subtracting fasting heat production (FHP) from HP (see text).

**Table 4**
Diet composition, growth performance and N and energy utilization in broilers ($n = 23$ diets)[1].

| Item | Mean | Min. | Max. | CV, % |
|---|---|---|---|---|
| Diet composition, % DM basis | | | | |
| CP | 24.2 | 20.8 | 28.4 | 9.9 |
| EE | 6.5 | 2.7 | 10.6 | 40.6 |
| Starch | 43.1 | 33.6 | 55.3 | 11.8 |
| CF | 3.9 | 2.2 | 6.6 | 32.0 |
| ADF | 5.7 | 3.3 | 8.8 | 28.9 |
| NDF | 10.7 | 7.0 | 17.2 | 25.5 |
| Ash | 6.5 | 5.5 | 8.7 | 12.0 |
| Ca | 9.2 | 8.2 | 10.2 | 6.3 |
| P, total | 6.6 | 5.6 | 7.7 | 10.9 |
| Growth performance | | | | |
| Initial BW, g | 686 | 678 | 695 | 0.7 |
| FI, g DM/d | 103 | 96 | 109 | 3.6 |
| BW gain, g/d | 89 | 82 | 94 | 3.7 |
| FCR, g DM/g | 1.16 | 1.04 | 1.26 | 4.7 |
| AME intake, kJ/d | 1573 | 1502 | 1618 | 2.0 |
| NE intake, kJ/d [2] | 1205 | 1126 | 1268 | 3.1 |
| AME/BW gain, kJ/g | 17.7 | 16.4 | 18.8 | 4.2 |
| NE/BW gain, kJ/g | 13.5 | 12.4 | 14.6 | 5.0 |
| Nitrogen balance, g/d | | | | |
| Intake | 4.0 | 3.4 | 4.7 | 11.2 |
| Retained | 2.9 | 2.5 | 3.3 | 8.1 |
| Retained, % of intake | 73.0 | 65.6 | 77.0 | 4.1 |
| Energy balance, kJ/kg $BW^{0.70}$ per day | | | | |
| FI, g DM/kg $BW^{0.70}$ per day | 110 | 102 | 117 | 3.5 |
| AME intake | 1682 | 1605 | 1731 | 2.2 |
| HP | 841 | 812 | 860 | 1.4 |
| RE | | | | |
| Total | 841 | 756 | 899 | 5.0 |
| As protein | 459 | 399 | 512 | 7.1 |
| As fat | 382 | 255 | 477 | 17.8 |
| HI[3] | 394 | 364 | 412 | 3.1 |
| NE intake | 1288 | 1203 | 1347 | 3.3 |
| Protein/fat ratio in RE | 1.28 | 0.88 | 2.05 | 27.2 |
| Respiratory quotient | 0.987 | 0.923 | 1.062 | 3.7 |
| Energy values, MJ/kg DM | | | | |
| GE | 19.20 | 18.40 | 20.18 | 2.8 |
| AME | 15.25 | 14.04 | 16.75 | 4.8 |
| AMEn | 14.28 | 13.02 | 15.67 | 5.2 |
| AMEs | 15.08 | 13.93 | 16.57 | 4.9 |
| NE | 11.68 | 10.53 | 13.19 | 6.2 |
| NEwu[4] | 11.42 | 10.28 | 12.61 | 5.7 |
| Energy utilization, % | | | | |
| AME/GE | 79.4 | 74.8 | 84.7 | 3.6 |
| AMEn/GE | 74.3 | 69.5 | 79.7 | 4.0 |
| AMEs/GE | 78.5 | 74.1 | 83.6 | 3.5 |
| NE/AME | 76.6 | 74.7 | 78.7 | 1.3 |
| NE/AMEn | 81.8 | 80.3 | 84.1 | 1.0 |
| NE/AMEs | 77.4 | 75.1 | 79.6 | 1.5 |

ADF = acid detergent fiber; AME = apparent metabolizable energy; AMEn = AME corrected for zero nitrogen retention in the body; AMEs = AME standardized (corrected with nitrogen retained in the body equal to 60% of nitrogen intake); BW = body weight; CF = crude fiber; CP = crude protein; CV = coefficient of variation; DM = dry matter; FCR = feed conversion ratio; EE = ether extract (or fat); FI = feed intake; GE = gross energy; HI = heat increment; HP = heat production; NE = net energy; NDF = neutral detergent fiber; RE = retained energy.

[1] Range of means per diet ($n = 23$; each mean corresponds to the average of 19 observations for the reference diet and 7 to 11 observations per diet for the other diets); data on performance, nitrogen balance and energy balance are expressed per bird.

[2] NE was estimated by subtracting HI from AME (see text).

[3] HI was calculated by subtracting fasting heat production (FHP) from HP (see text).

[4] NE as calculated from NE equation proposed by Wu et al. (2019) as follows: NE = (0.781 × AME) − (0.028 × CP) + (0.029 × EE) with NE and AME as MJ/kg DM and CP and EE as % of DM.

NDF diets and the highest values with the low DF and/or high starch diets. Energy efficiency of AME for NE averaged 76.6% with the highest value of 78.7% observed in the diet with high EE content and the lowest (74.7%) in a high DF and high CP diet.

### 3.3. Energy efficiency of dietary nutrients

The variations in metabolizability of diets and efficiency of AME for NE as described above result, in fact, from differences in the metabolizability and efficiency of the energy supplied by the different nutrients. It is then interesting to quantify the contribution of the different major energy-yielding nutrients to energy supply. This has been analyzed by linear regression using the mean measurement values of the 23 diets (Table 5). The coefficients for CP, EE and starch indicate the contribution of each nutrient to GE, AME, and NE and the ratios between the coefficients of each nutrient in AME and GE equations and in NE and AME equations can be assumed to correspond to the metabolizability of GE (i.e., AME/GE) and the efficiency of AME for NE (i.e., NE/AME), respectively. This approach indicates that 83%, 98% and 102% of GE of CP, EE and starch, respectively, was converted to AME and 73%, 87% and 81% of AME of CP, EE and starch was converted to NE. The energy contribution of the DF fraction of the diet, either estimated as residue 1 (Res1) or as NDF (Table 5) to AME was quite low (20%) and equal to zero for NE. In accordance with the mode of calculation of AMEn and AMEs, the only nutrient that was affected in terms of energy metabolizability or AME efficiency was CP. For instance, when based on AME value, the metabolizability of GE from CP was 69% while the efficiency of AMEn for NE of CP was 88%. Since AMEs and AME values were rather close, the efficiency values of CP were quite comparable for AMEs and AME. In line with these differences between nutrients for metabolizability of GE and efficiency of AME for NE as obtained from Table 5, energy efficiencies of AME/GE and NE/AME were dependent on diet chemical composition (Table 6).

### 3.4. Prediction of dietary AME and NE content

In agreement with high correlations between ME value and EE and DF (as NDF, ADF or CF) (Table 2) or the significant effects of EE, starch, or DF on AME/GE ratio (Table 6), the best predictors of AME were either CP, EE and starch without any DF indicator or EE and starch if one DF indicator was included. The highest coefficient value of EE in each AME equation that included DF was as expected. Rationally, the first predictor of NE in a stepwise model was AME. In agreement with the high correlations between NE/AME and CP, EE or DF indicators, the best NE predictions involved CP, EE and CF or ADF or NDF, in addition to AME content. The coefficient of AME in these equations is close to 0.81 and then quite comparable to the

**Table 5**
Contributions of diet energy-yielding nutrients (% DM basis) to GE, AME, AMEn, AMEs, and NE (MJ/kg DM basis) in broilers[1].

| Equation no. | Energy | Equation | | | | | | RSD |
|---|---|---|---|---|---|---|---|---|
| | | CP | EE | Starch | NDF | Res1 | Res2 | |
| 1 | GE | 0.224 | 0.390 | 0.171 | | 0.198 | | 0.077 |
| 2 | | 0.241 | 0.390 | 0.169 | 0.206 | | 0.149 | 0.052 |
| 3 | AME | 0.186 | 0.384 | 0.174 | | 0.039 | | 0.138 |
| 4 | | 0.183 | 0.384 | 0.174 | 0.038 | | 0.045 | 0.137 |
| 5 | AMEn | 0.154 | 0.377 | 0.170 | | 0.039 | | 0.124 |
| 6 | | 0.154 | 0.377 | 0.170 | 0.040 | | 0.037 | 0.124 |
| 7 | AMEs | 0.187 | 0.377 | 0.170 | | 0.039 | | 0.124 |
| 8 | | 0.187 | 0.377 | 0.170 | 0.040 | | 0.037 | 0.124 |
| 9 | NE | 0.135 | 0.334 | 0.141 | | 0.009 | | 0.141 |
| 10 | | 0.134 | 0.334 | 0.141 | 0.008 | | 0.011 | 0.141 |

AME = apparent metabolizable energy; AMEn = AME corrected for zero nitrogen retention; AMEs = AME standardized (corrected for nitrogen retained equal to 60% of nitrogen intake); CP = crude protein; EE = ether extract (or fat); GE = gross energy; NDF = neutral detergent fiber; NE = net energy; Res = residue; Res1 = the organic matter in the diets except CP, EE and starch; Res2 = Res1 minus NDF; RSD = residual standard deviation.

[1] The analysis was done using a linear regression model without intercept on means of the measurements on 23 diets.

**Table 6**
Prediction of efficiencies of GE for AME and AME for NE in broilers diets from their chemical composition (% DM basis)[1].

| Equation No. | Energy | Equation | | | | | | | RSD |
|---|---|---|---|---|---|---|---|---|---|
| | | Intercept | CP | EE | Starch | CF | ADF | NDF | |
| 11 | AME/GE | 30.4 | 0.52 | 0.92 | 0.71 | | | | 0.9 |
| 12 | | 62.3 | | 0.55 | 0.39 | −0.86 | | | 0.9 |
| 13 | | 65.2 | | 0.52 | 0.35 | | −0.75 | | 0.9 |
| 14 | | 65.3 | | 0.54 | 0.37 | | | −0.49 | 0.7 |
| 15 | NE/AME | 81.0 | −0.17 | 0.19 | | −0.39 | | | 0.5 |
| 16 | | 80.9 | −0.15 | 0.20 | | | −0.32 | | 0.4 |
| 17 | | 81.8 | −0.18 | 0.19 | | | | −0.20 | 0.5 |

ADF = acid detergent fiber; AME = apparent metabolizable energy; CF = crude fiber; CP = crude protein; EE = ether extract (or fat); GE = gross energy; NDF = neutral detergent fiber; NE = net energy; RSD = residual standard deviation.
[1] Equations from mean values per diet ($n = 23$ diets) originating from 235 individual measurements.

efficiency of starch AME for NE (81%), resulting in no significant contribution of starch in any NE equation. Crude protein and DF showed a negative impact on NE values whereas EE contributed positively to the NE values of the diets.

## 4. Discussion

In order to obtain an appropriate database for predicting the AME and NE values of diets according to their chemical composition, the nutrient levels should be variable and be representative of most practical situations that may include rather extreme diets in terms of nutrient levels and/or ingredient inclusion levels. In the specific case of NE prediction, the performance of the birds should also be quite comparable among diets with levels of performance that are representative or even higher than the breeders' recommendations in order to simulate the expected continuous improvement of performance due to genetic efforts and improved management of poultry production. Otherwise, the NE values of diets would be biased with potential impact on the coefficients of the NE prediction equation (Noblet et al., 2022). The results of our study indicate that most of the above criteria were met. Indeed, as in the studies of Wu et al. (2019) or Carré et al. (2014) with objectives similar to this study, the diets were highly variable in terms of ingredients and nutrients. These diets, eventually supplemented with glycine, tryptophan, valine, arginine, isoleucine and leucine in addition to lysine, methionine and threonine, were also adapted to high levels of performance (90 g ADG/bird on average; all values higher than 80 g/bird) that are superior to Aviagen targets (Aviagen, 2019). In agreement with this fast growth, daily N retention (2.9 g/d) was above the values reported in the literature (McCafferty et al., 2022; Musigwa et al., 2021a; Wu et al., 2019) at this stage of growth. In addition, the dietary N was used quite efficiently, since 73% on average was retained by the broilers with maximum values close to 77% for the low CP diets. Again, these values are equal to the maximum values reported in the literature (Khalil et al., 2022; Lopez and Leeson, 2007; Yang et al., 2020). With regard to chemical analyses of feeds, the contributions of nutrients to GE supply of diets (Table 5) are quite consistent with theoretical values or those obtained in similar regression models by Sauvant et al. (2004) or Noblet et al. (2023a), indicating that the chemical analyses of feeds in the present study are consistent and reliable. Overall, the experimental design of the study, including a relatively high number of diets, each being measured on at least 8 groups of birds over 5 consecutive days in the respiration chambers combined with diet specifications that allowed our broilers to achieve high levels of performance, should be adequate for establishing accurate and reliable NE prediction equations.

Daily feed intake, the primary response of the birds to the diet characteristics, was found to be influenced negatively by EE and positively by DF (CF, ADF and NDF) and consequently by the energy density of the diet (Table 2). The variations were attenuated when FI was expressed as AME or NE intake. As predicted, BW gain increased with increase in dietary CP but was not affected by DF (CF, ADF and NDF). Logically, FCR deteriorated in high fiber diets and improved in high EE feeds. These general observations that were not a primary objective of our study are consistent with the literature (Leeson and Summers, 2009; Mateos et al., 2012; Woyengo et al., 2023).

The average daily AME intake per kg $BW^{0.70}$ of 1.70 MJ in our study is higher than those reported in other similar studies involving a high number of diets with AME intake only 1.20 MJ per kilogram $BW^{0.70}$ in 1 to 21 d birds (Cerrate et al., 2019) and approximately 1.40 MJ per kilogram $BW^{0.70}$ in older (25 to 28 d) birds (Carré et al., 2013; Wu et al., 2019). However, numbers close to the present study were reported in the studies where few numbers of test diets (<10) per study were used (McCafferty et al., 2022; Morgan et al., 2019; Noblet et al., 2015; Sharma et al., 2021). These differences across the studies indicate the possible influence of diet chemical composition and age or genetic background of the animals on energy intake. However, daily HP values of 841 kJ per kilogram $BW^{0.70}$ are in line with other studies (McCafferty et al., 2022; Musigwa et al., 2021a; Wu et al., 2019), even though different methods (open circuit vs. closed circuit calorimetry system, age and number of birds, number of measuring days) were used across the studies. Consequently, HI values that were calculated by subtracting FHP values (Noblet et al., 2015) from HP were similar for these studies. Studies have reported HP values ranging from 49% to 63% of AME intake, with most studies obtaining values around 56% (Liu et al., 2017b; McCafferty et al., 2022; Morgan et al., 2019; Musigwa et al., 2021b, 2021c; Wu et al., 2019). The HP values in the current study, averaging 50% of AME intake, reflect a minimal loss of energy as HP in broilers. Consequently, RE values also averaged 50% of AME in our trial while lower proportions of AME were retained in most other studies (Morgan et al., 2019; Musigwa et al., 2021a, 2021b, 2021c; Wu et al., 2019).

The average efficiency of GE for AME (i.e., metabolizability) of 79% in the present study is close to the values (78%) reported by Cerrate et al. (2019) but approximately 6% higher than those reported by Carré et al. (2013) and Wu et al. (2019). Nevertheless, all the studies stated above, including the present study, agreed on the point that the metabolizability of GE is positively dependent on starch level and negatively on DF level of the diets. Differences in diet composition between studies may then generate differences in AME/GE ratio. Levels and sources of enzyme supplementation may also generate differences between studies for the metabolizability of GE in broilers (Cerrate et al., 2019; Musigwa et al., 2021a, 2021b; Noblet et al., 2022). Additionally, the high N retention coefficient of birds in the present study could also contribute to the higher efficiency of GE for AME. These latter observations also confirm that the commonly used AMEn concept (i.e., AME corrected for zero N retention) is not at all representative of the present situation of broiler production with AME values 5% to 7% higher than AMEn values (Table 3). A standardization of AME values for a level of N retention representative of most practical conditions and applicable to the total growing period should then be used (Cozannet et al., 2010; Noblet et al., 2022).

The efficiency of AME for NE averaged 77% (range: 75% to 79%) in the present study. These values are in good agreement with most previous studies where NE/AME values of 73% to 80% have been reported (Carré et al., 2014; Cowieson et al., 2019; Liu et al., 2017a, 2017b; McCafferty et al., 2022; Morgan et al., 2019; Musigwa et al., 2021a, 2021b, 2021c; Sharma et al., 2021; Wu et al., 2019). In contrast, lower efficiency values of AME for NE (67%) were reported by Cerrate et al. (2019) for a set of 10 diets; the age of the birds (1–21 d) and their rather low FI (1.2 vs. 1.7 MJ AME per kilogram $BW^{0.70}$ per day in our study) may contribute to such a low value. Although there was a good agreement across most studies, it is worth noting that differences between the studies in terms of trial design, diets characteristics, systems used for measurement of HP, number of days tested, age and genotype of birds and, most importantly, the value of FHP associated with the calculation of NE, may have contributed to differences between studies. Therefore, as suggested by Noblet et al. (2022), the comparison or the compilation of NE values from studies conducted under different methods and conditions may be inappropriate and should therefore be discouraged. An illustration is presented in Fig. 1A with measured efficiencies in our study that are clearly higher (2% on average) than those calculated from the results of Wu et al. (2019) while the same FHP literature value was considered in these 2 studies for calculating NE value of diets and comparable calorimetry measurements for evaluating HP were used. Several hypotheses including the genotype and the age of the animals, their behavior (level of physical activity), the calibration of the equipment for $O_2$ and $CO_2$ measurements or the FHP value that is actually different between the two groups of birds can explain the differences between the 2 studies. Unfortunately, their respective contributions cannot be quantified.

In addition to these differences between studies, the efficiency of AME for NE in poultry is affected by diet characteristics as suggested by our results and those also obtained in studies with a rather large number of diets per study (Carré et al., 2014; Cerrate et al., 2019; Wu et al., 2019) that agree on a negative effect of dietary CP and a positive effect of EE. These effects of nutrients on the diet efficiency in fact reflect differences between nutrients for the use of AME for NE, the highest values being obtained for fat (85% to 87%), the lowest for CP (50% to 73%) and intermediate for starch (78% to 81%) in the studies of Carré et al. (2014) and Wu et al. (2019) and in the present study. Again, the values obtained in the study of Cerrate et al. (2019) are lower than in the other studies, especially for starch (68%). However, the nutrients are ranked similarly (CP < starch < EE) in all studies. The intermediate value for starch explains the absence of significant contribution of this criterion in the prediction equations of NE/AME (Table 6). Higher values of AME efficiency for CP in the present study could be explained as a result of higher N retention. It is worth mentioning that a similar ranking between nutrients is observed in pigs (Noblet et al., 1994). One specificity of the present study, as suggested by the results of Cerrate et al. (2019), is the significant and negative effect of DF on the prediction of AME efficiency for NE. No direct biological explanation can be given for our result since, rather practically, DF is little digested in birds. However, it can be noticed that the equations proposed in Table 6 for NE/AME from our study are more precise (0.5% vs. 1.5% for RSD) than those proposed by Wu et al. (2019) and with more room for introducing additional but less significant predictors such as DF.

In agreement with our results concerning the effect of diet composition on NE/AME, diet NE value is primarily dependent on AME value, followed by CP and EE. Surprisingly and despite the direct effect of DF on AME, an additional and significant negative effect of DF on NE prediction was observed in our trial. This effect was also suggested in the results of Cerrate et al. (2019) but not in those of Wu et al. (2019) or Carré et al. (2014). As with the comparison of calculated and measured NE/AME ratios (Fig. 1A), the measured NE values of our diets are about 2% higher than those calculated with the equation of Wu et al. (2019). However, they are similarly ranked (Fig. 1B).

As done in other animal species, the NE equations established on complete feeds in our study can be used for the prediction of NE values of ingredients with the use of AME value and some chemical criteria without requiring the complicated and tedious in vivo measurement of NE of ingredients for broilers (Noblet et al., 2022). This approach is illustrated in Table 8 for 13 ingredients used in the

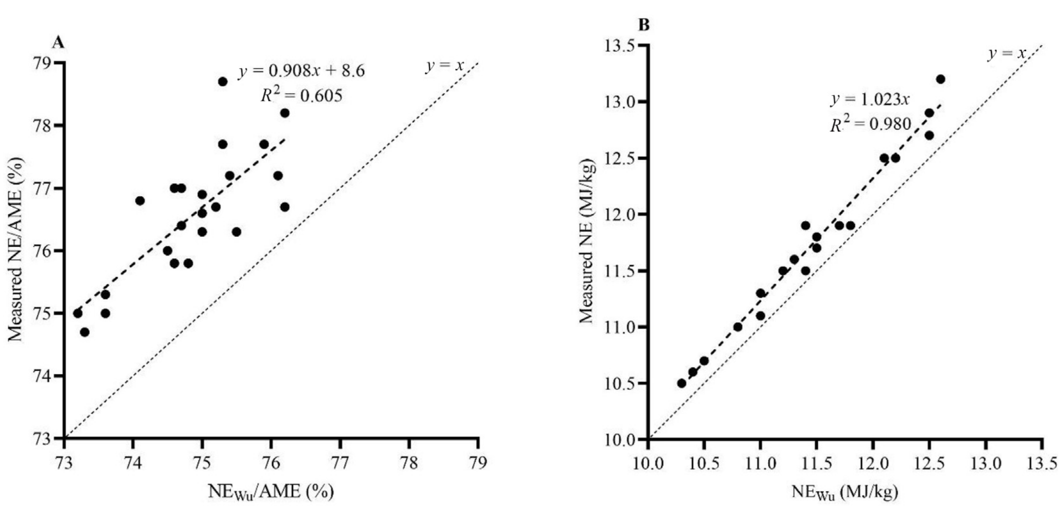


**Fig. 1.** Relationship between measured net energy (NE) value of the 23 diets from the present study and their NE values calculated from Wu et al. (2019). (A) Energy efficiency of apparent metabolizable energy (AME) for NE as measured in the present study vs. calculated efficiency of AME for calculated NE. (B) Measured NE values vs. calculated NE values. $NE_{Wu} = (0.781 \times AME) - (0.028 \times CP) + (0.029 \times EE)$ with NE and AME as MJ/kg DM and CP and EE as % of DM. CP = crude protein; EE = ether extract (or fat).

**Table 7**
Prediction of AME and NE content (MJ/kg DM basis) of broiler diets from chemical composition (% DM basis)[1,2].

| Equation No. | Energy | Equation | | | | | | | | RSD |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Intercept | AME | CP | EE | Starch | CF | ADF | NDF | |
| 18 | AME | 3.37 | | 0.150 | 0.346 | 0.139 | | | | 0.13 |
| 19 | | 12.46 | | | 0.241 | 0.050 | −0.236 | | | 0.13 |
| 20 | | 12.90 | | | 0.234 | 0.044 | | −0.187 | | 0.13 |
| 21 | | 12.46 | | | 0.244 | 0.054 | | | −0.104 | 0.13 |
| 22 | NE | | 0.811 | −0.026 | 0.020 | | −0.049 | | | 0.08 |
| 23 | | | 0.809 | −0.023 | 0.021 | | | −0.040 | | 0.07 |
| 24 | | | 0.815 | −0.026 | 0.020 | | | | −0.024 | 0.07 |

ADF = acid detergent fiber; AME = apparent metabolizable energy; CF = crude fiber; CP = crude protein; EE = ether extract (or fat); NDF = neutral detergent fiber; NE = net energy; RSD = residual standard deviation.
[1] From mean values of measurements on 23 diets.
[2] Composition is expressed as % of DM.

**Table 8**
Comparison between measured and calculated efficiencies of AME for NE of 13 ingredients in broilers.

| No. | Ingredient | CP, % | EE, % | Measured NE/AME, %[1] | Calculated NE/AME, %[2] | Calculated $NE_{Wu}$/AME, %[3] |
|---|---|---|---|---|---|---|
| 1 | Corn | 9.1 | 4.7 | 77.9 | 79.4 | 77.4 |
| 2 | Cassava pellet | 4.9 | 1.6 | 69.3 | 78.9 | 77.4 |
| 3 | Broken rice | 9.8 | 1.1 | 80.0 | 79.8 | 76.7 |
| 4 | Paddy rice | 9.8 | 2.6 | 79.4 | 76.4 | 76.7 |
| 5 | Wheat | 14.8 | 2.0 | 76.5 | 77.4 | 75.8 |
| 6 | Animal protein | 55.7 | 9.1 | 79.0 | 73.0 | 69.3 |
| 7 | Full fat soybean | 40.3 | 21.6 | 77.0 | 77.3 | 75.6 |
| 8 | Soybean meal | 54.1 | 1.4 | 71.4 | 69.4 | 66.8 |
| 9 | Canola meal | 40.1 | 2.0 | 55.4 | 66.1 | 67.9 |
| 10 | Rice bran | 14.7 | 19.6 | 79.5 | 78.8 | 79.0 |
| 11 | Wheat bran | 17.8 | 2.9 | 59.6 | 68.6 | 74.0 |
| 12 | Palm kernel meal | 17.7 | 8.0 | 74.0 | 68.9 | 77.4 |
| 13 | Palm kernel oil | – | 100.0 | 86.0 | 85.0[4] | 85.0[4] |

AME = apparent metabolizable energy; CP = crude protein; EE = ether extract (or fat); NE = net energy.
[1] AME and NE values of ingredients were obtained according to a multiple regression model applied on AME and NE values measured on 23 diets that were prepared from the 13 listed ingredients (see text and Noblet et al. (2022) for more details).
[2] Calculated for each ingredient as the ratio between its calculated NE value (Equation 24 in Table 7) and AME value as obtained from the multiple regression model.
[3] NE according to the equation by Wu et al. (2019). $NE_{Wu} = (0.781 \times AME) - (0.028 \times CP) + (0.029 \times EE)$ with NE and AME as MJ/kg DM and CP and EE as % of DM. AME values were from the multiple regression model.
[4] Fixed value suggested by Noblet et al. (2023b).

diets of the present study and whose AME and NE values were calculated according to a multiple regression method (unpublished results). As it can be extrapolated from observations on diets, the NE/AME ratio is the highest in pure fat sources (>85%) and the lowest in protein- and/or fiber-rich ingredients (65%–75%) and intermediate (80%) in cereals and protein- and fat-rich sources. The same hierarchy has been measured in some recent studies on poultry but with a very limited number of ingredients (Liu et al., 2017b). When the NE prediction proposed by Wu et al. (2019) is used (Table 8), slightly lower NE/AME values are obtained from our equation for the high DF ingredients in connection with the negative role of DF on NE/AME not observed in the study of Wu et al. (2019).

As for AME, our study was designed to measure the NE value of 13 ingredients according to the regression model as well. The levels of inclusion of these ingredients are given in Table 1. As explained by Noblet et al. (2022) for the regression method but also for the difference method, the accuracy of the estimation of AME or NE value of an ingredient is dependent on its mean and min–max levels of introduction, either on a DM basis or on an energy basis. This means that the accuracy should be the lowest for the high DF ingredients such as canola meal, rice bran, wheat bran or palm kernel meal that represent 2% to 3% of DM on average and 10% to 15% max in our study. Despite these constraints, the results of our approach indicate that the NE/AME values as measured for the 13 ingredients are quite comparable to those predicted from the NE prediction equation, including NDF as the DF predictor (Table 8). In other words, as already demonstrated by Noblet et al. (2023a) in pigs, the NE prediction equations obtained in broilers from measurements on diets are applicable to ingredients. However, some adjustments for very specific ingredients (pure fat, crystalline amino acids) should be done (Noblet et al., 2023b). Furthermore, either the predicted values or the measured NE/AME values of ingredients indicate that the efficiency of AME for NE in poultry is not constant with changes in the relative energy values of ingredients between the AME and NE systems, justifying the implementation of the NE concept in poultry.

## 5. Conclusion

This study evaluates the feed NE values and AME efficiency for NE of 23 balanced diets with a wide range of chemical compositions. The ultimate goal was to generate a set of equations that allow the prediction of NE values and AME efficiency of diets and raw ingredients based on their chemical compositions according to a simple and robust method. In the present study, the most representative equation for NE prediction is: NE (MJ/kg DM) = 0.815 × AME − 0.026 × CP + 0.020 × EE − 0.024 × NDF (AME as MJ/kg DM; CP, EE and NDF as % of DM); this equation is valid for both complete feeds and ingredients which is great progress when compared to recent studies in poultry proposing questionable measured NE values of ingredients (Noblet et al., 2023b). The coefficients of this equation indicate that the contribution of AME value to NE value is far greater than the contributions of the chemical criteria. It is then a high priority to have a precise AME system for an accurate prediction of the NE value. From this point of view, obtaining a representative AME value of feeds with standardization (AMEs) for a high efficiency of N gain (>60%) (Noblet et al., 2022, 2023b) is of pressing need. Our study also shows that the ranking between complete feeds or between ingredients differs in the AME and NE evaluation systems according to their chemical composition. Finally, there are only a handful of studies on feed NE values of broilers that are comparable based on the methodology, conceptual agreement, robustness of the trial design, genetics, and age of the animals. Therefore, it is appropriate to combine those studies and propose a more general set of NE prediction equations. In this regard, it is recommended to consider the suggestions by Noblet et al. (2023b) for further use of NE prediction equations for poultry.

## Author contributions

**Aye Cho Tay-Zar:** conceptualization, methodology, investigation, data analysis, writing original draft, reviewing/editing. **Manoosak Wongphatcharachai:** conceptualization, critical review of the manuscript, supervision. **Pairat Srichana:** conceptualization, critical review of the manuscript, supervision. **Pierre-André Geraert:** conceptualization, critical review of the manuscript. **Jean Noblet:** conceptualization, methodology, data analysis, writing original draft, critical review of the manuscript.

## Declaration of competing interest

We declare that we have no financial and personal relationships with other people or organizations that can inappropriately influence our work, and there is no professional or other personal interest of any nature or kind in any product, service and/or company that could be construed as influencing the content of this paper.

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