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Original Research Article

Re-evaluation of recent research on metabolic utilization of energy in poultry: Recommendations for a net energy system for broilers

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ABSTRACT

Different energy systems have been proposed for energy evaluation of feeds for domestic animals. The oldest and most commonly used systems take into account the fecal energy loss to obtain digestible energy (DE), and fecal, urinary and fermentation gases energy losses to calculate metabolizable energy (ME). In the case of ruminants and pigs, the net energy (NE) system, which takes into account the heat increment associated with the metabolic utilization of ME, has progressively replaced the DE and ME systems over the last 50 years. For poultry, apparent ME (AME) is used exclusively and NE is not yet used widely. The present paper considers some important methodological points for measuring NE in poultry feeds and summarizes the available knowledge on NE systems for poultry. NE prediction equations based on a common analysis of three recent studies representing a total of 50 complete and balanced diets fed to broilers are proposed; these equations including the AME content and easily available chemical indicators have been validated on another set of 30 diets. The equations are applicable to both ingredients and complete diets. They rely primarily on an accurate and reliable AME value which then represents the first limiting predictor of NE value. Our analysis indicates that NE would be a better predictor of broiler performance than AME and that the hierarchy between feeds is dependent on the energy system with a higher energy value for fat and a lower energy value for protein in an NE system. Practical considerations for implementing such an NE system from the commonly used AME or AME_n (AME adjusted for zero nitrogen balance) systems are presented. In conclusion, there is sufficient information to allow the implementation of the NE concept in order to improve the accuracy of feed formulation in poultry.

1. Introduction

The cost of feed represents an important part of the total cost of poultry production (>60%). In feed, protein is the most limiting component for growth, whereas in economic terms, energy accounts for at least 70% of feed cost (Pirgozliev and Rose, 1999). This economic importance and the direct effects of energy supply on animal performance in all domestic animal species have led to the development of different systems to express the energy value of feeds and the energy requirements of animals concomitantly. Not all gross energy (GE) consumed is retained by the animal as losses occur in the feces and urine, and as gases and heat. Based on these losses, different energy values and energy systems have been defined: digestible energy (DE) is the difference between GE intake and energy losses in the feces; metabolizable energy (ME) is the difference between DE intake and energy losses in urine and gases from digestive fermentation; and net energy (NE) is the difference between ME intake and heat increment (HI). In poultry, the feces

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and urine are excreted together, and hence only ME is commonly determined. In addition, in the fecal and urinary energy components, a fraction originates from endogenous secretions and the rest from the consumed feed. Subtracting these endogenous losses from the total losses allows the calculation of true ME (TME; Sibbald, 1982). This TME concept has been progressively abandoned over the past two decades. Today, the apparent ME (AME) has become the default system for measuring dietary energy values for poultry. In addition, the AME values for poultry are quite often standardized for a zero nitrogen (N) balance of the animal (AME_n), allowing comparison among growing and adult birds. Details on these different concepts and the associated methodologies were presented in the review of Noblet et al. (2022).

The research and development of NE systems over the past 70 years have varied according to the animal species: since the 1970s, it has been frequently used for ruminants; then in the 1990s, it was applied in pigs (Just, 1982; Noblet et al., 1994) with a successful use in practical feed formulation; and more recently, it was established in poultry (Cerrate et al., 2019; Carré et al., 2014; Tay-Zar et al., 2023; Wu et al., 2019), although its widespread practical application is yet to occur. However, since the NE systems are applied in feed formulation for ruminants and pigs, there is heightened interest by the global poultry industry to implement an NE system over the next few years.

The main purpose of this paper is to describe briefly the methods for evaluating the NE content of feeds for domestic animals in general and more specifically for poultry. Details on these methodological aspects have been given in a recent review paper (Noblet et al., 2022) and hence will only be described briefly. The most novel aspect of the current paper will come from the compilation of recent NE data obtained in broilers that proposes NE prediction equations, paving the way to transition from the AME system to a reliable NE system. Other comprehensive reviews on energy evaluation in poultry (Wu et al., 2020; Zaefarian et al., 2021) and in pigs (Noblet and van Milgen, 2004; Noblet et al., 2023) complement the views and opinions developed in the current paper.

2. Net energy: definitions and methodologies

The NE concept is rather old (Armsby and Fries, 1915) and has been used in domestic animals, rodents and humans. It is mostly based on the development of calorimetry methods, either direct or, more commonly, indirect techniques based on gas exchanges; comparative slaughter methods have also been used (Noblet et al., 2022). Net energy is defined as the ME content minus the HI originating from the energy cost of ingestion, digestion, and metabolic utilization of feed energy and the energy cost corresponding to a standard level of physical activity of the animal (Noblet et al., 2022). The NE to ME ratio (or k) corresponds to the efficiency of ME utilization for NE; it also corresponds to 1 − (HI/ME). The HI of a given energy intake in an animal is equal to its total heat production (HP) when fed minus its total HP when not fed, i.e., fasting HP (FHP); thus, NE is equal to ME − (HP − FHP) or (ME − HP) + FHP; since ME − HP is equal to retained energy (RE; as body protein and body lipid in growing birds or as eggs in layers), NE in producing animals is calculated as RE + FHP. RE can be estimated directly according to the comparative slaughter technique (CST) or calculated as the difference between ME intake and HP. The measurement or estimation of RE (or HP) and FHP are thus necessary for measuring the NE content of a feed; the concomitant measurement of ME intake is also required (Noblet et al., 2022).

As detailed by Noblet et al. (2022), the HI/ME ratio of a given feed depends on the ME intake level as well as on several animal, environmental and methodological factors. In addition, under most production conditions, ME intake is used to meet the requirements for maintenance and production (weight gain or eggs). But it is not possible to differentiate the metabolic utilization of feed ME between these different functions on a given animal. This means that HI/ME or k is usually obtained for the combined utilization of ME for maintenance and production. The practical consequence of these variations of HI or k, independent of feed characteristics, is that to relate the NE value of a series of feeds to only their chemical and physical characteristics, the measurement of NE value should be done under standardized methodological, nutritional, animal physiological and health, and management conditions. Thus, the comparison of NE values of feeds obtained under different animal and environmental conditions should be made with great caution, requiring a careful examination of the diet, animals, trial conditions and methodologies.

The measurement of NE values of numerous complete diets under similar animal, environmental and methodological conditions allows the construction of a database useable for calculating the relationships between the characteristics of the diets and their NE values. In such cases, linear regression models between dietary NE and some predictors are produced, the predictors being the digestible nutrient contents, or the DE or ME values plus some chemical indicators, or the chemical characteristics alone or even the near infrared (NIR) spectra of the diet. One equation established from one database and, eventually, different regression models from one database, define what is termed an NE system (Noblet et al., 2022). The development of such an NE prediction and then an NE system is technically complicated, time-consuming and costly; measurements on at least 20 diets with variable levels of nutrients as well as low correlations between their fat, protein, starch and dietary fiber levels are required to avoid inherent bias. Only when these conditions are met, will the NE system be robust and reliable, making it possible to be validated. As shown by Noblet et al. (1994; 2023) for pigs and detailed later in the current paper for poultry, such an NE system offers the possibility of calculating the NE value of any feed, complete diet or ingredient, as far as the predictors used in the equations are easily available and accurate. This alleviates the tedious measurements and uncertainties of evaluation of NE of individual ingredients.

The evaluation of dietary NE content requires measurements or estimations of RE and FHP. The energy gain in growing birds over a given experimental period can be evaluated as the difference between the energy content measured in BW at the end and at the start of the experiment (i.e., CST). In the case of layers producing eggs, the energy gain corresponds to the exported energy in eggs corrected for the changes in body energy content (Barzegar et al., 2019). The initial body energy content of the experimental animals is evaluated from contemporary and similar animals measured for their body energy content at the beginning of the trial. In most cases, the body energy content is measured after slaughter, grinding of the total body and measuring GE value in a representative sample of it (Carré et al., 2014). The energy content in the body can also be estimated on live animals using scanning methods such as the dual-energy X-ray absorptiometry (DEXA) method (Cerrate et al., 2019). The CST remains popular for poultry since it does not require any sophisticated equipment and it is quantitative, rather accurate and representative of practical conditions if conducted over a sufficiently long period; but it is more laborious and the response applies to the total experimental period with no possibility of a dynamic response of the animals over successive days or even short periods during 1 d.

The energy gain can also be obtained as the difference between ME intake of the bird and its HP. Heat production can be measured directly through direct calorimetry or, more commonly, estimated from indirect calorimetry through the measurement of oxygen consumption and carbon dioxide production in respiration chambers (Brouwer, 1965). Details on the different techniques and approaches for evaluating the gas exchanges have been given in the review of Noblet et al. (2022). Unlike the CST method, the indirect calorimetry systems allow measurements over short periods of time (i.e., daily) and have the potential for evaluating the HP related to the physical activity of the animals. However, one major concern for this indirect calorimetry method, especially in the quite frequently used open-circuit system, is the calibration of the system, especially with regard to the measurement of oxygen consumption that is rather difficult, complex and a potential source of large errors in the calculation of HP and subsequent NE evaluation.

The FHP of animals can be obtained by evaluating HP at several different ME intakes and calculating a regression between HP and ME intake that is extrapolated at zero ME intake. However, as observed in ruminants, calves and pigs (Koong et al., 1982; Labussière et al., 2011), this methodology provides estimates of FHP that are meaningless and, in all cases, markedly lower than the FHP values measured directly on animals after a moderate fasting duration that are highly preferable (Labussière et al., 2011). Therefore, as suggested by Noblet et al. (2015), FHP estimates for poultry should come from indirect calorimetry HP data obtained over 18 to 24 h after feed withdrawal with animals kept in the dark to reduce their physical activity and at thermoneutral conditions. However, under such conditions, there is still a "residual" level of physical activity included in that FHP estimate which represents a source of variability in the FHP estimate. The more sophisticated method proposed by van Milgen et al. (1997), which consists of modelling the decrease of HP and the contribution of physical activity HP over 24 h after feed withdrawal, generates an asymptotic HP that is assumed to correspond to FHP at zero physical activity. The FHP values thus obtained do not include any HP related to physical activity and are slightly lower than those obtained over a few hours after a minimum 18 h of fast at very low levels of physical activity (dark) (Noblet et al., 2015). In a compilation of FHP measurements obtained according to that methodology on more than 70 groups of birds, Noblet et al. (2015) recommended daily FHP values for growing broilers of about 450 kJ/kg $BW^{0.70}$.

Practically, the NE value of a given quantity of daily feed to an animal or a group of animals is calculated as the sum of their daily RE and their daily FHP, with the latter quantity corresponding to the average metabolic body size over the fed period multiplied by the FHP per kilogram of metabolic body weight. Daily data are further expressed as per kilogram of daily feed DM intake. A rather long list of technical points for implementing such measurements is given by Noblet et al. (2022) for getting reliable NE values. In short, for growing animals and a given trial or series of trials to be compared, it is suggested to use energy balance measurements in similar animals (i.e., same sex, same breed, and in the same body weight range), keep these animals within their thermoneutral zone, minimize variation in behavior, and feed them at about the same feed intake level with a balanced diet so that they can express their growth potential. If the indirect calorimetry method is used for HP measurement, a minimum of 2 full days of HP measurement would be required in growing broilers and slightly longer (4 d) in laying hens after a few days of adaptation to the equipment, the feed and the husbandry conditions. Under these circumstances, HP and NE data will be attributable only to dietary effects.

Finally, the literature suggests that the AME values of feeds in poultry differ between animal growth stages and species (Cozannet et al., 2010). Similarly, k values for a given feed may differ between these stages, suggesting that there should be as many NE values of feeds as different physiological situations within a species. That may then complicate the application of an NE system. However, the quality and potential of an energy system depend on its ability to rank the feeds correctly for predicting animal performance. Literature results suggest that, at least in pigs (Noblet et al., 2023), the ranking between feeds for k values is quite comparable between stages of production, even if the absolute values of k differ slightly. The observations of Barzegar et al. (2019) in layers and their comparison with corresponding results in broilers would suggest similar conclusions. This means that an NE system established at one stage of production can be used at any stage of production within a species as far as the main predictor of NE content (i.e. AME) in NE prediction equations is reliable and possibly specific to the stage of production or the poultry species (Noblet et al., 2022).

3. Evaluation of dietary NE in poultry

Several studies have been published over the last 10 years with the objective of establishing NE prediction equations for poultry (Carré et al., 2014; Cerrate et al., 2019; Noblet et al., 2015; Tay-Zar et al., 2023; Wu et al., 2019). All these studies were conducted in growing broilers fed balanced diets either with the CST method (Carré et al., 2014; Cerrate et al., 2019) or with the indirect calorimetry method, using either close-circuit chambers (Wu et al., 2019) or open-circuit chambers (Noblet et al., 2015; Tay-Zar et al., 2023). Another study involving 16 diets concerned laying hens with complete N and energy balances and partition between egg production and body reserves; specific NE prediction equations for laying hens have been produced (Barzegar et al., 2019). Other results have been produced by research groups in China (Liu et al., 2017, 2020, 2022; Ning et al., 2014), USA (Sung et al., 2023) and Peru (Moscoso-Munoz et al., 2020) but most of them were conducted in laying hens or adult cockerels, involved a small number of diets per trial and concerned mainly the measurement of NE of ingredients according to the difference method. In addition, most of these studies had some of the diets imbalanced with insufficient or excessive levels of protein and amino acids, thus not optimal for representative performance of the birds. Therefore, the combination of these latter results with those obtained on a large number of diets and in broilers was not possible. Only the former studies on one stage of production (i.e., broilers) with balanced diets are suitable for a compilation.

An initial analysis of the data in broilers indicates that the results of Cerrate et al. (2019) differ from the 4 other studies. Indeed, the NE/AME ratio of their 20 diets (10 diets without or with enzyme supplementation) averaged 67%, while it averaged 74%–76% for the other 4 studies (Tables 1 and 2). The average chemical composition of the diets is comparable between the studies. Such a difference in NE/AME values between the study of Cerrate et al. (2019) and the other studies cannot then be explained by differences in diet composition. As mentioned earlier, the NE value includes an estimate of FHP for its calculation. Cerrate et al. (2019) assumed FHP equal to 435 kJ/kg $BW^{0.75}$ while, in the other 4 studies, the FHP value of Noblet et al. (2015) was used (450 kJ/kg $BW^{0.70}$). The application of both estimates of FHP to the 1–21 d old birds of the study of Cerrate et al. (2019) generated negligible differences in daily FHP values and cannot then explain the lower NE/AME ratio of that study. However, this literature estimate of FHP used in the study of Cerrate et al. (2019) may be too low considering the type and the age (d 1–21) of birds used. In addition, perhaps the housing conditions potentially allowed higher activity levels and energy expenses for thermoregulation. Another possibility for the low NE/AME ratio is that AME intake in that study (1.2 MJ/kg $BW^{0.70}$) was markedly lower than in the other studies (1.5 to 1.7 MJ/kg $BW^{0.70}$) with a subsequent lower energy gain and, more importantly, a higher proportion of protein in the energy gain (75% vs. 45%–55% in the other studies). The lower efficiency of AME for energy gain as protein than for energy gain as fat (Sakomura, 2004) may then

Table 1
Energy balance data used in the prediction equations of NE in broiler feeds (mean/study and range of means per diet within each trial between parentheses).

Trial[1]	1	2	3
Diets (n)	23	19	8
Carbohydrases supplementation	+	+	−
Diets composition, % DM			
Ash	6.5 (5.5–8.7)	5.3 (4.7–6.3)	6.1 (5.8–6.5)
Crude protein	24.2 (20.8–28.4)	23.4 (18.5–29.9)	24.6 (21.2–26.9)
Fat	6.5 (2.7–10.6)	5.4 (1.6–8.9)	6.6 (1.4–10.3)
Starch	43.1 (33.6–55.3)	41.1 (30.4–47.2)	46.9 (41.4–56.9)
NDF	10.7 (7.0–17.2)	11 (7.1–18.2)	9.8 (8.3–13.4)
Broilers performance			
Mean BW, kg	0.91 (0.89–0.93)	1.68 (1.52–1.79)	1.41 (1.26–1.55)
Daily feed DM intake, g/bird	103 (96–109)	152 (137–171)	128 (111–137)
Daily BW gain, g	89 (82–94)	112 (104–122)	85 (75–94)
Feed conversion ratio, g DM/g	1.16 (1.04–1.26)	1.36 (1.21–1.55)	1.5 (1.35–1.62)
N balance, g/d per bird			
Intake	4.00 (3.41–4.74)	5.75 (4.34–7.59)	5.01 (4.22–5.69)
Retained	2.91 (2.50–3.28)	3.53 (3.08–4.05)	2.92 (2.55–3.14)
Retained, % N intake	73.0 (65.6–76.9)	62.1 (51.4–70.8)	58.5 (53.8–63.9)
Energy balance data, MJ/kg $BW^{0.70}$			
AME intake	1.682 (1.607–1.732)	1.477 (1.385–1.573)	1.674 (1.561–1.879)
Heat production	0.841 (0.812–0.858)	0.824 (0.803–0.845)	0.874 (0.837–0.920)
Fasting heat production	0.45	0.45	0.45
Energy gain	0.841 (0.756–0.899)	0.653 (0.540–0.761)	0.799 (0.690–0.975)
Protein gain	0.460 (0.397–0.510)	0.364 (0.318–0.414)	0.364 (0.331–0.397)
Respiratory quotient	0.987 (0.923–1.062)	1.029 (0.975–1.090)	1.032 (0.976–1.114)
Energy values, MJ/kg DM			
GE	19.20 (18.40–20.18)	19.27 (18.52–19.94)	19.21 (17.87–20.27)
AME	15.25 (14.04–16.75)	14.02 (12.36–15.89)	15.10 (14.30–16.36)
AME_n	14.28 (13.02–15.67)	13.23 (11.67–15.03)	14.31 (13.57–15.41)
AME_s	15.07 (13.93–16.57)	14.00 (12.41–15.82)	15.12 (14.35–16.30)
NE	11.68 (10.53–13.19)	10.45 (9.10–11.97)	11.26 (10.48–12.22)
Energy efficiencies, %			
AME/GE	79.4 (74.8–84.7)	72.7 (65.5–79.7)	78.6 (75.7–82.1)
NE/AME	76.6 (74.7–78.7)	74.5 (71.4–76.8)	74.6 (72.4–76.1)

NE = net energy; N = nitrogen; AME = apparent metabolizable energy; AME_n = AME adjusted for zero N balance; AME_s = standardized AME; GE = gross energy.
[1] Trial 1: adapted from Tay-Zar et al. (2023); trial 2: adapted from Wu et al. (2019); trial 3: adapted from Noblet et al. (2015) and unpublished data.

contribute to a lower NE/AME value of their diets. Overall, the study of Cerrate et al. (2019), even though it appears to have been conducted properly, looks rather different in terms of the efficiency of AME for NE with no clear and quantitative explanations for the differences. The combination of this study with the other ones was, therefore, not possible.

The 3 studies presented in Table 1 have been conducted with a common methodology based on indirect calorimetry measurements over 3 to 5 d with a common value for FHP (Noblet et al., 2015). However, the broilers differed in age, BW and genetic characteristics since different breeds were used and the studies were conducted in 2002–2012 (Noblet et al., 2015), 2012–2015 (Wu et al., 2019) and 2020–2022 (Tay-Zar et al., 2023) with marked differences in their growth potential due to intense selection over time. Finally, the equipment, housing conditions, calibrations and analytical procedures used for the measurements differed between the 3 studies with potential bias due to the location of the trials. In conclusion, even though a common approach was used in these 3 studies, it looks necessary to include a trial effect (direct or interactions) in the analysis of the results.

The study of Carré et al. (2014) is based on the CST method using 21 to 35 d old broilers and was conducted in the late 1990s. Measurements included growth performance, energy gain and its partition between protein and fat over a 14-d period; the results can be considered quantitative and reliable. As mentioned by Noblet et al. (2022), a validation step is required when proposing an energy system, the best validation being the response of the animals, in terms of energy efficiency variability between vastly variable diets, according to the energy system used. The study of Carré et al. (2014) could then offer excellent support for the validation of the three other more comparable studies (Table 1) that could be analyzed simultaneously in order to propose a robust NE prediction equation obtained from a rather large number of diets ($n = 50$) and three different environments whose direct and interactive effects can be included in the statistical analyses.

The characteristics of the 3 trials used in the statistical analyses are summarized in Table 1 and all details are available in the original publications. In brief, the study of Tay-Zar et al. (2023) (trial 1) is the most recent with fast-growing 3-wk-old broilers retaining more than 70% of their N intake on average and the diets varied widely in terms of ingredients (rice products, for instance) and nutrient levels; the metabolizability (AME/GE) of the diets and associated AME values and the N efficiency (N gain over N intake) were quite high. The studies of Wu et al. (2019) (trial 2) and Noblet et al. (2015) (trial 3) were conducted on heavier and older birds that retained about 60% of their N intake and a higher proportion of fat energy in their energy gain. The energy metabolizability in trial 3 was close to the values obtained in trial 1 but higher than in trial 2. This difference may be related to the lower fat level and/or the higher NDF content and/or the lower starch content in trial 2 in addition to the type of ingredients and the presence or absence of enzymes. Nevertheless, none of these hypotheses and their respective contributions can be quantified. In addition, the nutrient levels were not measured under the same conditions or with the same analytical procedures. An inevitable effect of the trial should then be considered in the analysis of these 3 trials. However, the variation in chemical composition within a location reflects the “true” variation of the nutrient contents. Overall, the range of chemical composition (as % of DM) is quite large with CP varying between 20% and 30%, fat between 2% and 10% and starch between

Table 2
Energy balance data used in the validation of the NE prediction equations (adapted from Carré et al., 2014; n = 30 diets; 21–35 d of age).

Item	Mean	Min.	Max.
Diets composition, % DM			
Ash	7.0	6.1	8.1
Crude protein	22.9	18.0	29.8
Fat	9.1	5.6	12.3
Starch	38.9	27.5	44.7
NDF	13.5	8.1	20.6
Broilers performance			
Mean BW, kg	1.16	1.10	1.22
Daily feed intake, g DM/bird	120	108	139
Daily BW gain, g/bird	69	59	76
N balance, g/d per bird			
Intake	4.37	3.58	5.30
Retained	2.18	1.69	2.46
Retained, % N intake	50	42	58
Energy balance data, MJ/kg $BW^{0.70}$			
AME intake	1.569	1.385	1.682
Heat production	0.866	0.808	0.954
Fasting heat production[1]	0.494	–	–
Energy gain	0.690	0.569	0.770
Protein gain	0.297	0.238	0.322
Fat gain	0.393	0.259	0.531
Energy values, MJ/kg DM			
GE	19.56	18.59	20.48
AME	14.13	12.03	15.62
AME_n	13.50	11.44	14.90
AME_s	14.25	12.15	15.79
NE[2]	10.79	9.26	12.38
NE calculated[3]	10.67	8.87	11.94
Energy efficiencies, %			
AME/GE	72.2	63.5	78.2
NE/AME	76.4	72.5	80.0

N = nitrogen; AME = apparent metabolizable energy; AME_n = AME adjusted for zero N balance; AME_s = standardized AME; NE = net energy; GE = gross energy.
[1] From van Milgen et al. (2001b).
[2] NE as measured by the authors.
[3] NE as calculated from Eq. 4 in Table 4.

30% and 57%. With regard to HP, energy balance and efficiency of AME for NE, the values are rather comparable and consistent between the 3 studies. Although a direct comparison is not possible, HP is not the highest in trial 1 according to the high AME intake, which results in an NE/ME ratio 2 points higher than in the other trials (77% vs. 75%).

The statistical analyses were conducted on the mean values per diet, each mean value originating from at least 5 individual measurements on small groups on birds. The first series of analysis investigated the contribution of the major nutrients constituting the organic matter (i.e., CP, ether extract (EE), starch and Residue; Residue being the difference between OM and the sum of CP, EE and starch) to GE, AME and NE supplies. A fractionation including also NDF and a corresponding Residue produced meaningless results because of the significant correlation between these 2 parameters and their energy contribution to AME and NE close to zero. Unfortunately, none of the 3 studies provided a more detailed fractionation quantifying the soluble and insoluble dietary fiber. In the first step, the trial effect was ignored and the regression procedure was conducted on each of the GE, AME and NE values (separate models) with estimates of the contribution of each major nutrient to GE, AME, NE or simultaneously on all three energy values (combined model) according to the method developed by van Milgen et al. (2001a) with estimates of GE, metabolizability and AME efficiency (NE/AME) for each nutrient. The key results and additional statistical indications are given in Table 3. Both regression models indicate GE contributions of the major nutrients comparable to their biochemical tabular values and reported data (Noblet and van Milgen, 2004). This confirms an acceptable consistency between the measured GE of the diets and their chemical composition among the trials, especially with fat and crude protein contents that deviate markedly from the GE content of the carbohydrate's fractions. In addition, the GE of Residue is consistent with results obtained on a large number of feeds (Noblet et al., 2022). Both methods also suggest that the AME/GE estimates are the highest for fat and starch (about 1.00), the lowest for the so-called Residue (0.20) and intermediate for crude protein (0.75). With regard to the NE/AME ratio, the agreement between the two calculation methods is also acceptable with the highest value for fat (0.85), the lowest for CP (0.65) and the intermediate for starch (0.80). The value for the Residue, which represents the non-starch carbohydrate fraction of the diet, is of limited accuracy and utility. Even though the calculation methods of NE/AME ratios for nutrients may differ between the studies, the values obtained in our compilation are close and ranked similarly to those proposed in broilers by Carré et al. (2014) (0.85, 0.68 and 0.78, respectively) and Cerrate et al. (2019) (0.86, 0.59 and 0.68, respectively), in pigs by Noblet et al. (1994) (0.85, 0.60 and 0.80, respectively) and even in catfish by Phan et al. (2021) (0.80, 0.64 and 0.58, respectively) for EE, CP and starch (digestible carbohydrates instead of starch for fish), respectively. Additional covariance analysis of the data for trials 1, 2 and 3 with trial as a fixed effect and chemical indicators as covariates also indicates significant differences between the mean energy values for the AME and NE prediction equations between trials (the highest values for trial 1 and the lowest for trial 3) but the coefficients of the nutrients were not significantly different between the trials. Compared with trial 3, AME and NE values in trial 1 were 0.75 and 0.96 MJ/kg DM higher for the same chemical composition, whereas in trial 2, the corresponding increases were 0.24 (not significant) and 0.38 MJ/kg DM, respectively (data not shown). These conclusions are consistent with the above comments on AME/GE and NE/AME variations between the studies, with trial 1 cumulating higher AME/GE and NE/AME ratios. This also means that the trial effect should be considered in the establishment of a common NE prediction.

The quantities of digestible nutrients in the diets were not available for the studies used in the compilation. Consequently, the only possible NE prediction model was to be based on the AME content plus some chemical indicators (Table 4). A first stepwise procedure suggested that, as found in the study of Tay-Zar et al. (2023), NE values in broiler diets could be predicted from dietary AME, CP, EE and NDF contents; but, as shown in Table 3, a covariance model indicated that the coefficient of AME was significantly affected by the trial number with a higher value for trial 1. The other coefficients of the covariance analysis were not significantly different among the trials. These findings are consistent with the higher NE/AME ratio obtained in trial 1. Our proposal is then to consider that the most appropriate coefficient of AME should be the weighted average of the coefficients obtained for the 3 trials according to the number of observations per trial. The final equation with AME, CP, EE and NDF as predictors of NE in broiler diets is shown in Table 4 (Eq. 4). Another simplified equation without the NDF factor obtained according to a covariance model and with a negligible deterioration of the accuracy of the prediction (0.12 vs. 0.11 MJ/kg DM for residual standard deviation [RSD]) is also proposed (Eq. 3). Finally, the amount of nutrients expressed relative to AME (g/MJ) might also be used in order to predict NE content (Eq. 5); in this case, no fiber indicator contributed significantly to the NE prediction equation. However, the lack of a better characterization of the dietary fiber fraction of the OM (soluble and insoluble fiber, for instance) for the compiled results makes such a conclusion premature.

Compared with the equation proposed by Wu et al. (2019), Eq. 4 includes dietary fiber (i.e., NDF) as an additional predictor. As in

Table 3
Prediction of energy values in broilers: combined analysis of 3 trials[1].

Item	AME	CP	EE	Starch	Residue	NDF	RSD
Separate models[2]							
GE		0.226	0.395	0.172	0.192		0.11
AME		0.175	0.403	0.171	0.036		0.45
NE		0.117	0.343	0.137	0.017		0.47
AME/GE		0.77	1.02	1.00	0.19		
NE/AME		0.67	0.85	0.8	0.47		
Combined model[3]							
GE		0.231	0.398	0.172	0.193		
AME/GE		0.77	1.02	1.00	0.19		0.38
NE/AME		0.67	0.85	0.80	0.47		
AME		0.175	0.403	0.171	0.036		
NE		0.117	0.343	0.137	0.017		
Prediction of NE value[4], kcal/kg							
Trial 1	0.813						
Trial 2	0.797	–0.026	0.015	-		–0.018	0.11
Trial 3	0.793						

AME = apparent metabolizable energy; EE = ether extract; RSD = relative standard deviation; GE = gross energy; AME = apparent metabolizable energy; NE = net energy.

[1] See Table 1 for details of each trial; energy values as MJ/kg DM and chemical composition as % of DM.

[2] Linear regression models with all nutrients of organic matter (zero intercept; Residue = dry matter – (ash + CP + EE + starch); the AME/GE and NE/AME ratios are calculated as the ratio between the coefficients of each nutrient in the NE, AME and GE equations). Covariance analyses with trial as a fixed effect indicate a significant effect of trial in the AME and NE equations (RSD: 0.32 and 0.28 MJ, respectively; trial 1 > trial 2 > trial 3) with no significant interaction effect between nutrients and trial (results not shown).

[3] Simultaneous adjustments of the 3 linear regression models (van Milgen et al., 2001b) describing GE, AME and NE as follows: $GE = \Sigma(a_i \times Nut_i)$, $AME = \Sigma(a_i \times b_i \times Nut_i)$ and $NE = \Sigma(a_i \times b_i \times c_i \times Nut_i)$ with Nut_i as one of the 4 nutrients, a_i as the GE of each nutrient, b_i as the AME/GE ratio and c_i as the NE/AME ratio; AME is then calculated as GE multiplied by the estimated AME/GE and NE is obtained as AME multiplied by the estimated NE/AME.

[4] From a covariance model including AME, CP, EE and NDF as covariates and trial as a fixed effect (and zero intercept) with the coefficient of AME dependent on trial effect; all coefficients are significantly different from zero ($P < 0.05$) and the coefficient of AME is significantly affected by trial ($P < 0.05$).

Table 4
NE prediction equations for poultry.

Item	Diets (*n*)	Equation[1]	RSD	Source[2]
Broilers				
Eq. 1	23	NE = 0.815 AME − 0.026 CP + 0.020 EE − 0.024 NDF	0.07	1
Eq. 2	19	NE = 0.781 AME − 0.028 CP + 0.029 EE	0.21	2
Eq. 3	50	NE = 0.805 AME − 0.034 CP + 0.015 EE	0.12	3
Eq. 4	50	NE = 0.804 AME − 0.026 CP + 0.015 EE − 0.018 NDF	0.11	3
Eq. 5	50	NE = 0.801 AME − 0.043 CP-AME + 0.008 EE-AME	0.11	3
Laying hens				
Eq. 6	16	NE (MJ) = 0.781 AME − 0.046 CP + 0.069 EE	0.39	4

RSD = residual standard deviation; NE = net energy; AME = apparent metabolizable energy; CP = crude protein; EE = ether extract.

[1] Energy as MJ per kilogram DM and chemical composition as % of DM. CP-AME and EE-AME are CP and EE contents as grams of CP or grams of EE per MJ AME, respectively.

[2] Sources: 1, Tay-Zar et al. (2023); 2, Wu et al. (2019); 3, compilation of data in broilers of Tay-Zar et al. (2023), Wu et al. (2019) and Noblet et al. (2015 and unpublished data), and see Tables 1 and 3 and text for explanations on the compilation; 4, Barzegar et al. (2019).

pigs (Noblet et al., 1994) and other previous NE equations in poultry (Table 4), the CP and dietary fiber contents negatively affect NE values while fat has a positive effect. The same trends were also observed for laying hens but with higher "correction factors" due to CP and EE (Table 4; Barzegar et al., 2019). The starch content never achieved the level of significance due to its coefficient being included in the coefficient of AME. This is logical since dietary starch represents more than 50% of the diet AME supply on average. These positive and negative effects of nutrients on NE prediction are consistent with the differences between nutrients for NE/AME as found in the literature and in Table 3 for the present analysis: lowest for CP, intermediate and close to the total diet for starch and highest for EE.

The study of Carré et al. (2014) consists of 3 series of 10 diets whose AME values were measured using the total excreta collection method on a group of birds and then the NE values were evaluated on another contemporary group of birds using the CST method over the 21–35 d of age period. A summary of the key results is presented in Table 2. Overall, despite the differences due to bird age and diet composition, the data are comparable to those measured in the 3 trials used in this compilation. A rather interesting point in that study is that the mean measured NE value is very close to the mean NE calculated from Eq. 4 in Table 4 (1% difference; Table 2). Furthermore, the agreement is also quite satisfactory for the 30 diets used in the study with a slope between measured and calculated NE values being 1.01 (Fig. 1), which is consistent with the 1% difference in the mean NE values. In addition, the difference between the measured and calculated NE values of the 30 diets is not significantly related to any chemical criteria. These observations represent the first validation of Eq. 4 proposed in Table 4 for predicting the NE value of broiler diets.

A second step in the validation approach comes from the feed efficiency results of the same study (Table 5). Indeed, the quality of a feed evaluation system rests on its ability to predict the response of the fed animals whatever the diet composition. In the case of energy systems, their quality can be measured through the feed efficiency criteria that can be expressed in different ways with the variability of the responses between the diets being as low as possible. When applied to the data of Carré et al. (2014), the coefficient of variation (CV, %) of the quantity of feed or energy per kilogram of BW gain is logically reduced when moving from feed weight or GE to AME, AME_n or NE; no improvement is observed from the conventional AME and AME_n systems to an NE system. A more precise evaluation of the feed efficiency is given by the amounts of feed energy per unit of energy gain in the body of growing animals, with or without adjustments for the composition of BW gain. Data in Table 5 indicate that the CV of energy efficiency is reduced when moving from GE to AME or AME_n and further to NE. In addition, as illustrated in Fig. 2, the NE cost of body energy gain is directly dependent on the composition of energy gain in connection with a higher cost of energy for protein energy than for fat energy (Sakomura, 2004). In another word, it is a lower efficiency of AME for energy gain as protein than for energy gain as fat. The additional adjustment of the NE requirement per unit of energy gain for the same proportion of energy gain as protein energy (43% in the present trial) contributes to a marked reduction of the CV that becomes quite low for the set of 30 diets. The exclusion of two extreme diets (2 and 6; Carré et al., 2014) would further reduce the CV to 1.6%. These observations on energy efficiency were based on NE values as measured by the authors. The same calculations with NE as calculated from Eq. 4 (Table 4) and measured AME values provide the same conclusions, the CV being slightly higher than that of the measured NE values. In conclusion, the results of that

Table 5
Feed efficiency and energy efficiency in broilers: effect of energy system (adapted from Carré et al., 2014; $n = 30$ diets; 21–35 d of age; see other results in Table 2).

Item	Mean	CV, %	Min.	Max.
Feed cost of BW gain				
Feed/BW gain, kg DM/kg	1.76	9.2	1.52	2.05
GE/BW gain[1], MJ/kg	34.3	8.0	30.3	38.7
AME/BW gain[1], MJ/kg	24.6	5.3	22.6	29.1
AME_n/BW gain[1], MJ/kg	23.6	5.6	21.5	28.1
NE/BW gain[1], MJ/kg	18.8	5.5	16.8	22.3
Feed energy cost of BW energy gain				
GE/energy gain[1], MJ/MJ	3.10	9.6	2.66	3.78
AME/energy gain[1], MJ/MJ	2.22	4.5	2.06	2.48
AME_n/energy gain[1], MJ/MJ	2.12	4.4	1.96	2.35
NE/energy gain[1], MJ/MJ	1.70	3.6	1.62	1.85
NE/energy gain[2], MJ/MJ	1.70	2.2	1.65	1.80
NE/energy gain[3], MJ/MJ	1.68	3.7	1.56	1.83
NE/energy gain[4], MJ/MJ	1.68	2.9	1.57	1.77

CV = coefficient of variation; GE = gross energy; AME = apparent metabolizable energy; AME_n = AME adjusted for zero nitrogen balance; NE = net energy.
[1] Energy values as measured by authors.
[2] NE as measured by the authors and energy gain efficiency adjusted for the same protein/fat ratio (Fig. 3).
[3] Calculated from Eq. 4 in Table 4.
[4] NE as calculated from Eq. 4 in Table 4 and energy gain efficiency adjusted for the same protein/fat ratio (see text and Fig. 3).

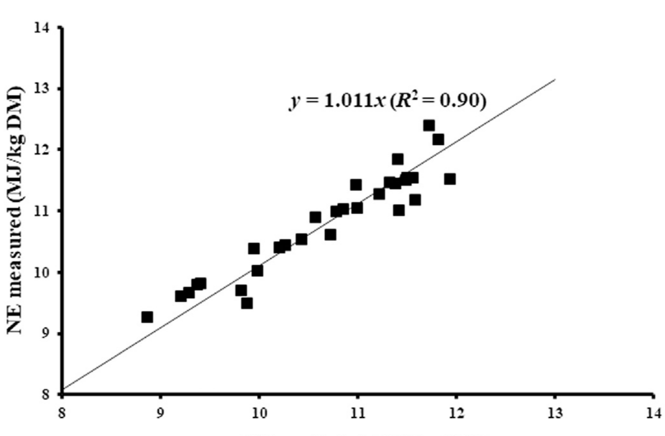

Fig. 1. Relationship between NE measured in 30 diets fed to broilers (Carré et al., 2014; Table 2) and NE calculated according to NE prediction Eq. 4 (Table 4). NE = net energy.

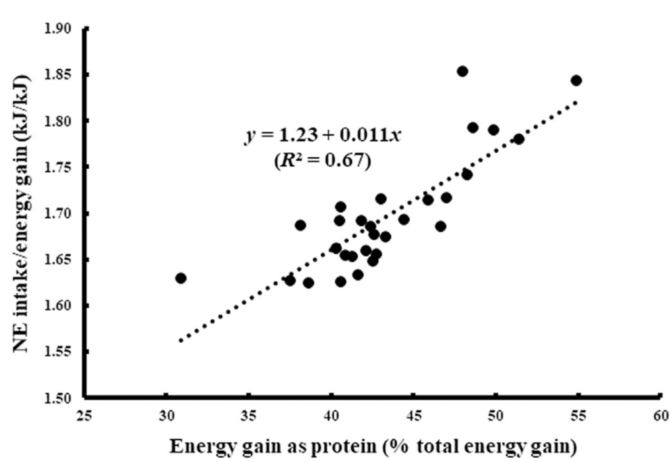

Fig. 2. Relationship between (measured) NE intake of body energy gain (kJ/kJ) and the proportion (%) of energy gain as protein in total energy gain (adapted from Carré et al., 2014; Tables 2 and 5). NE = net energy.

balance trial confirm the superiority of an NE system for predicting the response of birds to energy supply, especially with the NE prediction equation developed from the compiled data of 3 trials. This conclusion agrees with those of Zou et al. (2021) that the NE system as proposed by Wu et al. (2019) was better for predicting feed efficiency in growing chickens than the AME system. Finally, in the comparison of energy systems, it is important to take into account the composition of BW or energy gain for getting a reliable response. In agreement with Wu et al. (2019), this means that the measurement of dietary NE value of feeds under extreme or unbalanced environmental and dietary conditions with production performance deviating greatly from the breed standard can generate irrelevant and useless results. This also illustrates that the so-called caloric efficiency (BW gain per unit of energy intake) proposed by Cemin et al. (2020) in a pig trial where changes in body composition between feeds are ignored should not be used for estimating the NE values of feeds (Zhang et al., 2020).

The impact of the energy system on the energy value of ingredients for broilers is illustrated in Table 6 with the NE value calculated according to Eq. 4. This table also allows the comparison of the response of growing broilers and growing pigs. Whatever the species, the ranking of feeds differs depending on the energy system with the NE system ranking fat-rich sources higher and protein-rich (and fiber-rich) ingredients lower compared with the ME or the DE systems. The change is moderate for starch-rich feeds. For poultry, it is common to express the energy value of ingredients as AME adjusted for zero N balance (AME_n), even though it means nothing from a biological point of view. As the correction of AME to zero N retention for AME_n imposes about 4% to 5% penalty on the AME values of high protein ingredients (Lopez and Leeson, 2007), such penalty coincides with the lower NE/AME of high protein ingredients (Barzegar et al., 2019; Wu et al., 2019). Therefore, relative energy values of ingredients on an AME_n basis rank rather comparable to the NE basis, except for fat rich raw materials.

The NE values of ingredients for poultry have been measured in a few studies covering a very limited number of ingredients (Table 7). As indicated above for diets, a “trial effect” is real, often making NE values between ingredients not comparable if the measurements are done by different research groups. In addition, most measurements have been conducted with inappropriate diets, and the levels of the ingredients are different from what would occur in a balanced diet to meet the requirements of the birds, which may lead to inaccurate NE values as it occurs for AME values (Noblet et al., 2022; Wu et al., 2020). Overall, the use of measured ingredient NE values should then be considered with caution. However, in spite of these limitations, all results confirm the highest efficiency of AME for NE in pure fat sources (85%), the lowest efficiencies for soybean meal (60%–70%) and intermediate values for cereals (65%–75%). These values are close to those calculated in Table 7 for a few major ingredients used in poultry diets. This further encourages the viability of using an NE system in poultry feeds.

Table 7
Efficiency of AME for NE of ingredients in broilers: literature survey[1].

Study/Ingredients	NE/AME, %	Comments[2]
Cerrate-Fernandez et al. (2012)		
Corn	75	Broilers; CST; regression method
Soybean meal	59	
Barley	69	
Oil	87	
Liu et al. (2017)		
Corn	79	Breeding cocks; indirect calorimetry; difference method
Soybean meal	64	
Ning et al. (2014)		
Corn	65	Laying hens; indirect calorimetry; difference method
Corn DDGS	58	
Wheat bran	53	
Barzegar et al. (2019)		
Corn	75	Laying hens; indirect calorimetry; regression method
Wheat	74	
Soybean meal	62	
Canola oil	92	
Moscoso-Munoz et al. (2020)		
Corn	68	Broilers; CST; difference method
Wheat bran	73	
Soybean meal	57	
Fish meal	56	
Oil	86	
Tay-Zar et al. (2023)		
Corn	78	Broilers; indirect calorimetry; regression method
Soybean meal	72	
Oil	86	

DDGS = distillers dried grains with solubles.
[1] Each study considered in that table has produced NE values on at least 2 ingredients.
[2] Stage of production; method for energy gain measurement (comparative slaughter technique [CST]); calculation method for energy utilization of ingredients.

In conclusion, literature data allow us to propose a validated NE system for broilers whose practical utilization is more accurate in predicting the performance of birds than the conventional AME or AME_n system. However, it should be stressed that the measurement of NE value of diets and, more importantly, of ingredients is rather complex with the potential of producing wrong, inaccurate and non-additive energy values being high.

4. Practical considerations

Feed formulation requires accurate and reliable energy values of ingredients. Unlike in the pig industry that widely uses NE values,

Table 6
Relative energy values of ingredients in broilers according to the energy evaluation system (comparison with pigs).

Item	Broilers[1]				Growing pigs[2]			
	AME_n	AME_{60}	NE	NE/AME_{60}	DE	ME	NE	NE/ME
Diet[3], MJ/kg	12.28	12.90	9.73	75.5	14.70	14.11	10.65	75.5
Ingredients[3]								
Vegetable fat	307	292	327	85	235	244	289	89
Corn	110	107	110	78	100	102	108	80
Wheat	101	99	100	76	97	98	101	78
Wheat bran	56	57	49	65	66	65	63	72
Soybean meal	77	85	76	67	102	98	80	62

AME_n = AME adjusted for zero nitrogen balance; NE = net energy; DE = digestible energy; ME = metabolizable energy.
[1] AME_n values according to INRAE-CIRAD-AFZ (2019); AME_{60} corresponds to AME adjusted for 60% nitrogen intake as retained in the body (Noblet et al., 2022); NE calculated according to Eq. 4 in Table 4 with AME equal to AME_{60}; chemical composition of ingredients corresponds to values of INRAE-CIRAD-AFZ (2019).
[2] According to Noblet et al. (1994) and INRAE-CIRAD-AFZ (2019).
[3] Diet and ingredients energy values adjusted to 90% DM, except for vegetable fat (100%); for ingredients, values as percentage of diet energy value in each system; the diet corresponds to a combination (DM, % of DM) of corn (31.5%), wheat (31.5%), wheat bran (6%), fat (4%), soybean meal (25%) and minerals and vitamins (2%).

the poultry industry largely uses the AME or AME_n systems for evaluating the energy of ingredients (Wu et al., 2020) with most feeding tables providing only AME_n values (CVB, 2021; INRAE-CIRAD-AFZ, 2019; Rostagno et al., 2017). However, the AME_n value based on a zero-N retention, even though it is reliable and standardized, does not represent what happens in poultry because 50% to 70% of N intake is retained in the body or in eggs. For AME values, they are often derived from measurements that involve vastly different N efficiency values, keeping in mind that measured AME values depend on the proportion of N intake that is retained in the body or in eggs. The situation is most exacerbated for high protein ingredients and associated high protein diets as measured N efficiency values are far below the common N efficiency measured in practical (and low CP) diets (Abdollahi et al., 2021). Consequently, AME_n values of ingredients, either in feeding tables or in publications, are probably more reliable and consistent than AME values that depend on the type of animals and the experimental methods that have been quite variable between trials, research organizations, etc. In practical feed formulation for poultry, the dietary N level is minimized, especially with the increased use of low crude protein diets for minimizing the N wastage and the dependence on protein rich ingredients. Under these conditions, the N retained in the body represents 60% or more of the N intake. This ratio concerns all the ingredients used in the diet preparation, which suggests that the AME value of all ingredients should be standardized (AME_s) at that level of N efficiency in order to be representative of the reality of poultry production. The method for recalculating AME_n value from AME (and N efficiency) value or AME_s value from AME_n value has been described by Cozannet et al. (2010) or Noblet et al. (2022). As an example, AME_s is equal to AME_n + (0.034 × N content × N efficiency), with AME values as MJ/kg DM, N content as gram of N per kilogram of DM and N efficiency being at least 0.60 according to common poultry diets and modern poultry genotypes; the 0.034 coefficient corresponds to the energy (as MJ) released by 1 g of N as uric acid. It should also be mentioned that the N efficiency levels will increase with both the improvement of the amino acid composition of the diet (and the associated reduced CP content) and the genetic selection of the animals. Further or specific adjustments of AME_s values may then be needed in the future for taking into account these changes in N efficiency.

The NE prediction equations proposed in Table 4 for broilers have been obtained with high N efficiency values and then AME values were close to the AME_s concept. Furthermore, under practical formulation conditions, the N efficiency is maximized, averaging 60% under most production conditions. It is then proposed to use the NE prediction Eq. 3, 4 or 5 presented in Table 4 with AME_s values of ingredients calculated, as described above, from their AME_n values and, eventually, from their AME values and (if available) N efficiency values. In the case of pure fat sources, a ratio of 0.85 between NE and AME is preferable to using the general NE prediction equations. Similarly, the NE content of synthetic amino acids proposed for pigs can be used for poultry (EvaPig, 2020; Noblet et al., 2004). Finally, the NE equation proposed in Table 4 includes NDF as a predictor. If not available, NDF may be estimated from another dietary fiber indicator (crude fiber, ADF, NSP, total dietary fiber) and the ratio between NDF and the available dietary fiber indicator that can be estimated for any ingredient from feeding tables or literature. Eq. 3 without any dietary fiber predictor can also be used. This new method of calculating NE in poultry ingredients based on AME_n, AME_s and one NE equation allows the implementation of the NE system for broilers without any further complicated, time-consuming and expensive measurements. The NE values thus obtained are fully additive, consistent and useable in least-cost formulation.

The effect of age on the metabolizability of GE (either AME_n/GE or AME/GE) has been documented recently in broilers (Khalil et al., 2021, 2023; Sung et al., 2023), but the effect remains unclear and the magnitude of the variation with age is rather small (less than 2%). From a practical point of view and until further clear evidence, the effect of BW could be ignored. The only significant and important effect of age is when growing broilers are compared to adult cockerels, in which case, the metabolizability of GE is higher (Cozannet et al., 2010) in adult cockerels. Even though adult birds are not used routinely in production conditions, it should be pointed out that AME (i.e., AME_n) values involving adult cockerels frequently end up in feeding tables, adding additional variation to the already inaccurate AME values for broilers. Finally, the AME value of feeds in broilers can differ in laying hens and in other major poultry species (turkeys, ducks) (Cozannet et al., 2010). However, the available literature is insufficient for proposing a ME system specific to these birds at present, although there is good work for at least laying hens (Barzegar et al., 2019; Cozannet et al., 2010). The metabolizability of GE can also be modified by processing technologies (particle size, pelleting, extrusion, etc.) or by the use of feed additives (enzymes, probiotics, etc.) (Wu et al., 2020). Even though it is an important area for present and future improvements of the energy value of feeds for poultry, it is not within the scope of the current paper.

The effect of the growth or production stage on the efficiency of ME for NE has been little studied in poultry. Liu et al. (2022) investigated it but they used different diets for 14 to 16 and 28 to 30 d old broilers, and 45-wk-old laying hens, making comparison between production stages difficult. One possibility is to use the data of Barzegar et al. (2019) and Wu et al. (2019) to compare young male broilers with laying hens as these two studies were conducted under similar measurement conditions. The study of Barzegar et al. (2019) involved 16 diets fed to laying hens and measured for their NE contents. The variability of diet composition was lower than for the broiler study (Wu et al., 2019) described in Table 1. This variability is attenuated by the high level of ash in the laying hen diets (18% vs. 6% in DM, on average). The calculated NE value of these diets according to Eq. 4 (Table 4) is 2.5% (or 0.23 MJ/kg DM) higher than the measured value, on average. The use of Eq. 5 (Table 4), more appropriate for diets with such a high ash content, attenuates the difference (1.8%). In addition, as indicated in Fig. 3, the difference is the highest for the

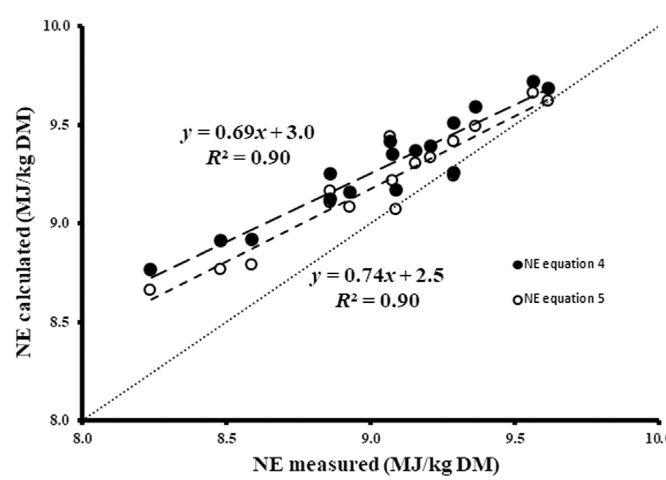

Fig. 3. Relationship between NE measured in laying hens (16 diets; Barzegar et al., 2019) and NE calculated according to NE prediction Eq. 4 and Eq. 5 (Table 4). NE = net energy.

low-energy diets, the superiority of the calculated NE values being significantly ($P < 0.05$) dependent on the dietary fat content. This observation on the effect of fat is consistent with the marked difference of the coefficients for EE in the NE prediction equation proposed by Barzegar et al. (2019) for laying hens and Eq. 3 applicable to broilers (Table 4). This difference in fat energy utilization between broilers and laying hens would suggest using a specific equation for layers. However, additional studies are needed to quantify fat utilization and metabolism differences between broilers and layers taking into account the fact that dietary fat in laying hens is largely exported in the egg. In the absence of such studies providing comparative energy efficiency responses in broilers and layers to dietary fat, the use of the NE equation established in broilers to layer feeds may be plausible. Similarly, there is no information yet quantifying the potential NE/AME ratio changes over the growing period in broiler chickens that might be associated with some changes in the composition of energy gain (protein/fat ratio) and the feed intake level (as a multiple of the maintenance energy requirements) with BW increase. The studies used in our compilation have been carried out in about the middle of the growing-finishing production and it can be accepted that the results are representative of the total feed consumed by the birds. Therefore, the equations proposed in Table 4 can be applied at any stage of production. In the future, the concomitant changes in AME value and NE/AME ratio with BW or other production factors might be taken into account but the mathematical approaches and the parameters set for the models need to be quantified and easily available at the production level.

As for metabolizability of GE, the efficiency of AME for NE may be changed by feed processing technologies or the use of feed additives. However, this area of research, despite being highly promising, is insufficiently documented for including these potential changes of NE/AME ratio in the evaluation of NE content of ingredients and complete diets. As suggested above for laying hens, it is then recommended to use Eq. 3 or 4 (or 5) in any situation for NE estimation of poultry feeds but with AME_s values of ingredients that may change with some animal factors and, more importantly, with dietary factors such as particle size, pelleting or the addition of enzymes.

A last practical point for implementing an NE system is the definition of the energy requirements of animals on an NE basis. The diet example used in Table 6 for getting the ranking of ingredients between energy systems suggests that the NE/AME ratio in both pigs and broilers is 75%–76%. This range also corresponds to the mean NE/AME ratio found in the broiler studies detailed in Table 1 (i.e., 75.5%). The simplest method for migrating the AME recommendations to NE recommendations is to multiply the ME values by 0.755 in order to get the NE basis for poultry. However, this simple approach will not provide an accurate and representative conversion of AME to NE in many cases. A more refined method may then consist in calculating the NE/AME ratios of the different standard types of diets used in practice at the time of energy system change when formulated with an AME system. Each standard NE/AME ratio is then used for evaluating the NE recommendation of each type of diet from each commonly used AME recommendation. In the specific situation of poultry, attention must be paid to the AME system that is used, the above coefficients being valid for AME_s (or AME) but not for AME_n. In the case of AME_n used as the starting point, the same approaches can be done with an average NE/AME_n ratio equal to 0.79 (AME_n equals 95% of AME_s; Tables 1 and 2) for the simplified method or calculated NE/AME_n ratios of different standard types of practical diets for the more refined approach. These new NE recommendations are then used for the least-cost formulation of diets on an NE basis.

5. Conclusions

The re-analysis of recent poultry literature data has generated NE prediction equations that have been validated in another major NE study. These NE equations, therefore, are ready to be used. An original method for calculating the NE value of ingredients for poultry via the commonly used AME_n value and the standardization of AME value (AME_s) is proposed. The change from AME systems to an NE system re-ranks feedstuffs with higher relative values for fat sources and lower relative values for protein sources in the NE system. From a methodological point of view, measuring NE is rather complex and should be done under highly controlled conditions in terms of environment, diet composition and level of performance of the animal. These methodologies should be used for specific studies where the efficiency of AME for NE might be affected, such as the use feed additives, feed processing technologies, animal factors (age, breed, species), and environmental factors (health and climate). However, the routine measurement of NE values as an attempt to tabulate NE values for individual ingredients is fraught with difficulties and is of little reliability and it should be avoided. Only the regression method, if correctly used, may have a degree of utility (Noblet et al., 2022). The best solution for evaluating NE of ingredients is to precisely quantify their AME content according to different methods including the use of feeding tables, NIR techniques, wet chemistry constituents, in vitro evaluations or in vivo measurements. These AME values are then used in the NE prediction equations proposed in the current paper. Finally, it is strongly recommended that the industry moves to an NE system to take advantage of its ability to offer a more accurate representation of dietary energy and better predict animal performance than the ME system.

Author contributions

Jean Noblet: conceptualization, data curation, drafting manuscript; **Aye-Cho Tay-Zar:** data curation; **Shu-Biao Wu:** critical review of the manuscript; **Pierre Cozannet:** statistical analyses, critical review of the manuscript; **Pairat Srichana:** critical review of the manuscript; **Pierre-André Geraert:** critical review of the manuscript; **Mingan Choct:** 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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