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REVIEW

Commercial poultry feed formulation: current status, challenges, and future expectations

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SUMMARY
Feed formulation has gone through vast improvements from simple hand formulations to computerised formulations using modern software equipped with advanced capabilities, which allows for high accuracy, easy integration, and flexibility. In general, modern commercial feed formulations are based on the concept of 'least-cost' and produced using linear programming. Several challenges are encountered when formulating feeds, such as nutrient variability, ingredient shortages, and ingredient price fluctuations. Adopting innovative technology has helped nutritionists overcome most of the challenges that they face. In the future, poultry feed formulation is likely to receive more enhancements like implementing the true protein and net energy system and considering advanced profit-maximising models. Such enhancements should maximise profitability, meet nutritional needs more accurately, and reduce environmental pollution for more sustainable poultry production.

KEYWORDS
Feed; feedstuffs; commercial; ingredients; nutrition

Introduction

Commercial poultry production has gone through numerous events and enhancements since the beginning of the 20th century until nowadays, where the industry is fully mature. Advances in the fields of genetics and nutrition over the years were regarded as the major reasons for the emergence of the modern poultry industry. Considerable progress in the science of nutrition was made in the 20th century. In the early 20th century, the importance of minerals and vitamins in poultry nutrition was beginning to be understood (Kaupp 1918; Mitchell, Kendall, and Card 1923). Protein need for poultry was well recognised in the early 20th century, but it was not until the middle of the same century when it was realised that the dietary need should be for the constituent amino acids (AA) not protein *per se*, and since then intensive research has been conducted on AA requirements for all classes of poultry at different ages (Dougherty 1923; Almquist 1960; Elwinger et al. 2016). Successful work at the Connecticut Agricultural Experiment Station in the late 1940th led to the formulation of a high-energy broiler diet, which was regarded as the first modern diet for poultry (Scott, Matterson, and Singsen 1947). Feed formulation in the early days was primitive and formulas were very simple, containing

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very few ingredients to meet the requirements of few nutrients. Simple feeds were formulated using hand formulation techniques such as simple equations or Pearson's square, and both were done with pencil and paper. In the early 1950s, electronic computers capable of solving complex mathematical problems were introduced, and soon after, poultry nutritionists realised the need for computerised formulations (Fisher and Schruben 1953). Early reports demonstrated the feasibility of formulating least-cost diets based on linear programming (LP) technique (Swanson 1955; Katzman 1956; Hutton 1958). The LP has been an essential tool in formulating commercial poultry feeds since then and has been preferred over other techniques, mainly due to its simplicity.

The least-cost formulation is the procedure of finding the optimal combination of ingredients that meets the nutritional requirements (minimum specifications) at the lowest cost possible. As the definition implies, the basic elements of the formulation process could be listed as the nutrient composition of ingredients, ingredient prices, and nutritional requirements. Missing any of these essential elements will render the feasibility of producing a formula impossible. Feed formulation has received much attention because feed is the most expensive input in poultry production, and profitability is dependent on it. However, the poultry literature is lacking detailed and updated review articles on feed formulation. Therefore, this review aims to describe the various programming techniques used in the formulation of poultry feeds and summarise the current status of the fundamental elements of feed formulation: composition, ingredient prices and nutritional requirements. Moreover, challenges encountered during the feed formulation process and the future expectations are covered in this review.

Feed formulation techniques

Commercial poultry feeds are typically formulated using the LP, which produces least-cost feeds. The LP is very simple to use and can handle very complicated situations, allowing the user to find the cheapest combination of ingredients that meets the minimum specifications of several nutrients by solving a series of linear constraints simultaneously using simplex algorithm. The basic mathematical constraints that represent the LP in commercial feed formulation software as detailed by D'Alfonso, Roush, and Ventura (1992) are:

$$\text{minimise} \sum\nolimits_{j=1}^{n} c_j x_j \tag{1}$$

subject to

$$\sum\nolimits_{j=1}^{n} a_{ij} x_j \leq b_i \tag{2}$$

$$\sum\nolimits_{j=1}^{n} a_{ij} x_j \geq b_i \tag{3}$$

$$x_j \leq d_j \tag{4}$$

$$x_j \geq d_j \tag{5}$$

$$x_j \geq 0 \tag{6}$$

$$\sum\nolimits_{j=1}^{n} x_j = 1 \tag{7}$$

Where

j: one of the several ingredients comprising the formula
n: total number of ingredients
x_j: fraction of the j^{th} ingredient
c_j: cost of the fraction of the j^{th} ingredient
a_i: concentration of the i^{th} nutrient
b_i: minimum or maximum specification of the i^{th} nutrient
d_j: minimum or maximum specification of the j^{th} ingredient

Nonlinear programming, sometimes referred to as stochastic nonlinear programming (SP), is an optimisation procedure based on probability distribution and is used in situations of high uncertainty, such as nutrient variation in feedstuffs. Nutrient variability is characterised by a non-linear nature because the statistical variance is nonlinear and cannot be solved by a typical LP model. To increase the confidence level of meeting the minimum specifications, the linear constraints 2 and 3 should be modified to derive nonlinear constraints, which can be incorporated in commercial feed formulation software.

$$\sum\nolimits_{j=1}^{n} u_{ij}\, x_j + Z_i \sqrt{\sum\nolimits_{j=1}^{n} \sigma_{ij}^2\, x_J^2} \geq b_i \tag{8}$$

$$\sum\nolimits_{j=1}^{n} u_{ij}\, x_j + Z_i \sqrt{\sum\nolimits_{j=1}^{n} \sigma_{ij}^2\, x_J^2} \leq b_i \tag{9}$$

Where the variable Z_i is the standard normal deviate corresponding to the desired probability of success. Constraint 8 is used to maximise essential nutrients like lysine, whereas constraint 9 is used to minimise non-nutritive compounds like fibre.

The traditional formulation models utilised in the poultry industry guarantee the least-cost feeding but may not be the most profitable models. Since the 1950s, several efforts have been made to demonstrate the feasibility of including profit-maximising models in formulations but were largely ignored. The profit-maximising techniques aim at finding the optimal balance between feed costs and returns that maximises profitability, not just minimising feed costs. Besides the information needed by the LP model, the profit-maximising techniques require the user to know the shape of the response curve of the birds to the nutrient of interest and the product value (meat, eggs, *etc.*). Thus, to arrive at the correct economic decision using these models, the right performance data, as well as the correct economic data, are required. The producer has to know exactly how the birds will perform, what he/she will have to pay for feed, and at what prices the products will be sold for. A group at the University of Georgia (GA, USA) proposed a nonlinear quadratic model to specify the optimal broiler feeds that maximise production (Miller, Arraes, and Pesti 1985; Pesti, Arraes, and Miller 1986). In their work, the optimum levels of protein and energy in the finished feed were considered as a function of feed cost and growth performance, and the model demonstrated some savings compared to the traditional LP. Another nonlinear model was proposed by Guevara (2004) that identifies the optimal formula for maximum margin over feed cost. This model takes into account technical performance data as a function of the energy density of feed, feed cost, and broiler value, and showed possible savings compared to the LP. Emmans, Fisher, and Gous developed an optimisation approach (Gous 2004; EFG SOFTWARE 2021) that combined three interacting elements: A linear programming based feed formulation model, a broiler growth model and an optimiser. The basis of this approach was to simulate the growth of a given flock of broilers based on a diet formulated by the formulation program and a nutrition optimiser. Other factors like genetic parameters, environment and stocking density are taken into account, and an objective function (e.g. margin over feed cost) is eventually optimised. Recently, Talpaz et al. (2013) developed complex models to predict the optimal energy and AA concentrations that maximise margin over feed cost. Their models are very powerful in that a wide range of experimental information such as using different broiler genotypes and marketing at different ages is incorporated. Broiler response to crucial nutrients like energy and essential AA should be curvilinear and exhibit a phenomenon known as diminishing returns (Almquist 1953). Therefore, the profit-maximising techniques are more appropriate than the traditional LP formulations, especially in markets where there are fluctuations in the values of inputs and outputs. It is worth noting that profit-maximising models may be adopted by integrated poultry producers and farmers to maximise profits. However, for feed manufacturers, the traditional least-cost formulations may still be the target.

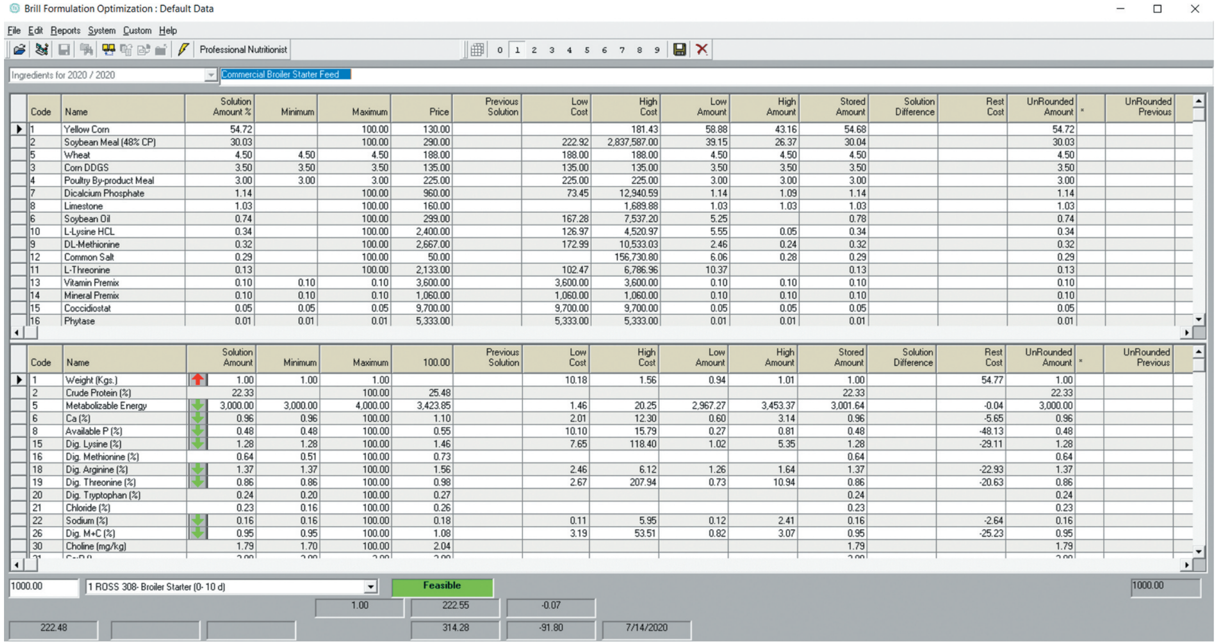
Feed formulation software varies in complexity from very sophisticated software like Brill Formulation® (Format Solutions, MN, USA), BESTMIX® (Adifo Software, Maldegem, Belgium), Allix^3 (A-SYSTEMS, Versailles, France), Concept5 (CFC Tech Services, MN, USA) or Afos (AFOS, Inc., NE, USA) to very simple Excel spreadsheets (Microsoft Corporation, WA, USA) such as WUFFDA 2.1 (Pesti et al. 2016). The simple spreadsheet gave almost the same solution to a commercial broiler starter feed as the sophisticated Brill software (Figures 1 and 2). However, commercial software packages are equipped with advanced optimisation engines that support complex calculations and a large volume of data and support multiple plants, products, and users. Furthermore, commercial software comes with advanced capabilities such as cloud computing, multi-blending, economic analysis (e.g. what-if analysis, parametric analysis), nonlinear optimisation, label generation, and report generation. The availability of cloud technology has provided many advantages to the feed industry, like granting the employees of the same company access to a common database from any device besides information sharing between the formulation system and the customers. As opposed to the classical optimisation of one formula at a time (single-blending), multi-blending allows the user to optimise a large number of formulas simultaneously to optimise the use of limited resources (*e.g.* allocation of a limited quantity ingredient). The smart labelling feature can allow users worldwide to make automated product labels, which can be compliant with regulations. In the modern feed industry, formulation software can be integrated with other systems such as quality control, enterprise resource planning or mill management to improve the precision of the nutritional matrix values, automate the entire product order-to-cash process, assist in ingredient purchase, provide real-time data on ingredient pricing and availability, and improve tractability. Formulation software suppliers will continue improving the formulation solutions to meet the growing demands of the ever-evolving industry.

Nutrient composition of feed ingredients

Nutritionists can analyse ingredients using wet-chemistry methods, use a faster technique like Near-Infrared Reflectance Spectroscopy (NIRS), or rely on published tables. The wet chemistry analysis is very accurate in determining ingredient compositions, but it can be time-consuming and costly. The NIRS can offer a rapid prediction of many nutrients such as total and digestible AA, crude protein (CP), and energy. However, the accuracy of the NIRS measurements depends on analytical data (sample number and diversity) from wet chemistry. The published tables contain nutrient contents as averages originated from many laboratory analyses. Currently, many sources supply valuable information on ingredient compositions such as the INRA-CIRAD-AFZ feed tables (INRA CIRAD and AFZ [2017] 2020), Feedipedia (INRA CIRAD AFZ and FAO [2012] 2019), Aminodat® (2016) series (Evonik; Essen, Germany), Premier Atlas (Premier Nutrition, Staffordshire, England) and the Australian Feed Ingredient database, AFiD (Moss 2020). Moreover, advanced formulation and management software allow access to ingredient composition databases, containing a large volume of data.

In some parts of the world, nutritionists base their formulations on published tables because it is impractical to analyse each batch of ingredient for all nutrients. However, this practice is not recommended as ingredients are quite variable in nutrient quality. Nutrient variability is an important characteristic of feedstuffs. For instance, the CP concentrations in subsequent batches of soybean meal (SBM) coming to a feed mill are not expected to be similar. The genetic background of soybean, agricultural conditions (e.g. fertilisation rates), stressors (e.g. drought), processing conditions (e.g. chemical vs. mechanical extraction), hull inclusion, sampling, and laboratory analysis are among the factors that contribute to the variability in SBM. While the variability of nutrients in grains and oilseeds are reasonable, processed products like poultry by-product meal, bakery meal, and fish meal, are characterised with greater variability due to the variable raw materials used in processing. Thus, these by-products require frequent analysis to evaluate their quality.

Typically, a traditional broiler formula in the U.S. and many Latin American countries contains corn, SBM, soybean oil (or poultry fat), DDGS, poultry by-product, salt, monocalcium phosphate, calcium carbonate, synthetic AA, vitamin premix, trace mineral premix, antibiotic growth promoter, coccidiostat and choline chloride (Mavromichalis 2020). Other ingredients, such as sorghum, soft wheat, and canola, are available. The U.S. modern broiler formulas are similar to the traditional formulas but with vegetable proteins only and without antibiotics or coccidiostats and supplemented with antimicrobial replacements such as organic acids (Mavromichalis 2020). Modern European broiler formulas are very similar to the modern U.S. formulas, but wheat (corn can be used too) is generally the major cereal (Mavromichalis 2020). Other ingredients like rapeseed meal, wheat middlings, and fishmeal are utilised in Europe. Exogenous enzymes such as phytase, xylanase, and beta-glucanase can be utilised in the formulas above to maximise nutrient digestibility.



Ingredients for 2020 / 2020

Commercial Broiler Starter Feed

Code	Name	Solution Amount %	Minimum	Maximum	Price	Previous Solution	Low Cost	High Cost	Low Amount	High Amount	Stored Amount	Solution Difference	Rest Cost	UnRounded Amount	*	UnRounded Previous
1	Yellow Corn	54.72		100.00	130.00			181.43	58.88	43.16	54.68			54.72		
2	Soybean Meal (48% CP)	30.03		100.00	290.00		222.92	2,837,587.00	39.15	26.37	30.04			30.03		
5	Wheat	4.50	4.50	4.50	188.00		188.00	188.00	4.50	4.50	4.50			4.50		
3	Corn DDGS	3.50	3.50	3.50	135.00		135.00	135.00	3.50	3.50	3.50			3.50		
4	Poultry By-product Meal	3.00	3.00	3.00	225.00		225.00	225.00	3.00	3.00	3.00			3.00		
7	Dicalcium Phosphate	1.14		100.00	960.00		73.45	12,940.59	1.14	1.09	1.14			1.14		
8	Limestone	1.03		100.00	160.00			1,689.88	1.03	1.03	1.03			1.03		
6	Soybean Oil	0.74		100.00	299.00		167.28	7,537.20	5.25		0.78			0.74		
10	L-Lysine HCL	0.34		100.00	2,400.00		126.97	4,520.97	5.55	0.05	0.34			0.34		
9	DL-Methionine	0.32		100.00	2,667.00		172.99	10,533.03	2.46	0.24	0.32			0.32		
12	Common Salt	0.29		100.00	50.00			156,730.80	6.06	0.28	0.29			0.29		
11	L-Threonine	0.13		100.00	2,133.00		102.47	6,786.96	10.37		0.13			0.13		
13	Vitamin Premix	0.10	0.10	0.10	3,600.00		3,600.00	3,600.00	0.10	0.10	0.10			0.10		
14	Mineral Premix	0.10	0.10	0.10	1,060.00		1,060.00	1,060.00	0.10	0.10	0.10			0.10		
15	Coccidiostat	0.05	0.05	0.05	9,700.00		9,700.00	9,700.00	0.05	0.05	0.05			0.05		
16	Phytase	0.01	0.01	0.01	5,333.00		5,333.00	5,333.00	0.01	0.01	0.01			0.01		

Code	Name		Solution Amount	Minimum	Maximum	100.00	Previous Solution	Low Cost	High Cost	Low Amount	High Amount	Stored Amount	Solution Difference	Rest Cost	UnRounded Amount	*	UnRounded Previous
1	Weight (Kgs.)	↑	1.00	1.00	1.00			10.18	1.56	0.94	1.01	1.00		54.77	1.00		
2	Crude Protein (%)		22.33		100.00	25.48						22.33			22.33		
5	Metabolizable Energy	↓	3,000.00	3,000.00	4,000.00	3,423.85		1.46	20.25	2,967.27	3,453.37	3,001.64		-0.04	3,000.00		
6	Ca (%)	↓	0.96	0.96	100.00	1.10		2.01	12.30	0.60	3.14	0.96		-5.65	0.96		
8	Available P (%)	↓	0.48	0.48	100.00	0.55		10.10	15.79	0.27	0.81	0.48		-48.13	0.48		
15	Dig. Lysine (%)	↓	1.28	1.28	100.00	1.46		7.65	118.40	1.02	5.35	1.28		-29.11	1.28		
16	Dig. Methionine (%)		0.64	0.51	100.00	0.73						0.64			0.64		
18	Dig. Arginine (%)	↓	1.37	1.37	100.00	1.56		2.46	6.12	1.26	1.64	1.37		-22.93	1.37		
19	Dig. Threonine (%)	↓	0.86	0.86	100.00	0.98		2.67	207.94	0.73	10.94	0.86		-20.63	0.86		
20	Dig. Tryptophan (%)		0.24	0.20	100.00	0.27						0.24			0.24		
21	Chloride (%)		0.23	0.16	100.00	0.26						0.23			0.23		
22	Sodium (%)	↓	0.16	0.16	100.00	0.18		0.11	5.95	0.12	2.41	0.16		-2.64	0.16		
26	Dig. M+C (%)	↓	0.95	0.95	100.00	1.08		3.19	53.51	0.82	3.07	0.95		-25.23	0.95		
30	Choline (mg/kg)		1.79	1.70	100.00	2.04						1.79			1.79		

1000.00

1 ROSS 308- Broiler Starter (0- 10 d)

Feasible

1.00

222.55

-0.07

222.48

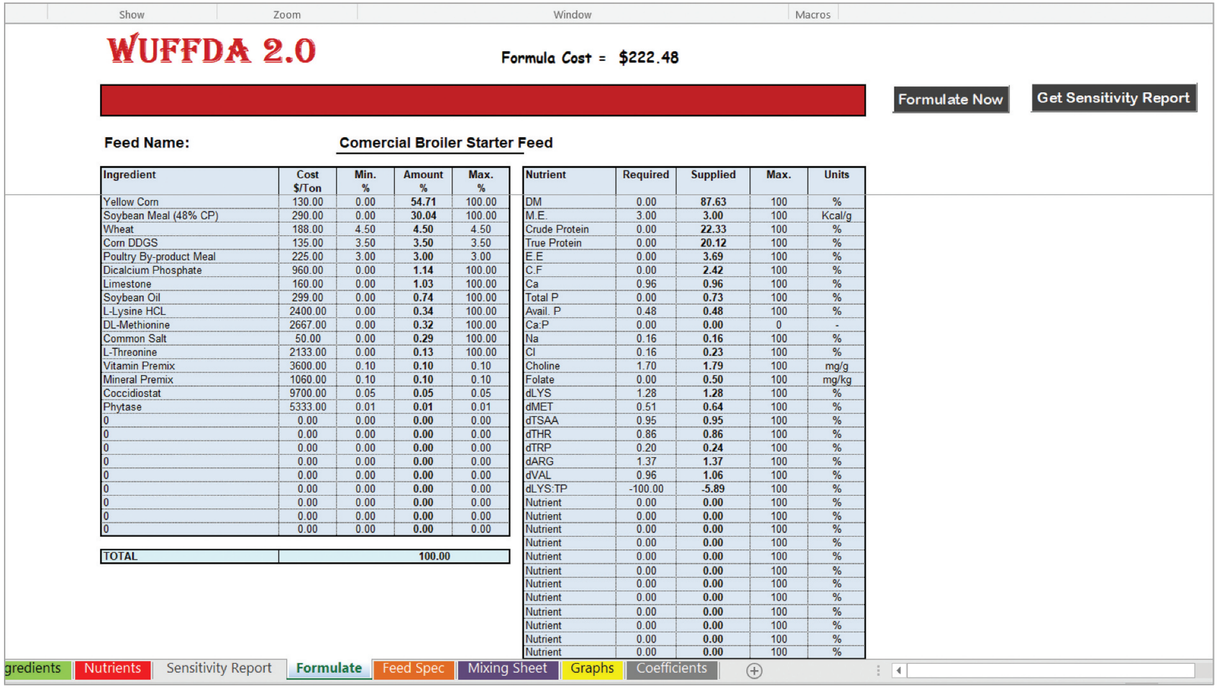
314.28

-91.80

7/14/2020

1000.00

Figure 1. Optimisation of a commercial broiler starter feed using Brill Formulation® (Format Solutions, MN, USA).



Formula Cost = $222.48

Feed Name: Comercial Broiler Starter Feed

Ingredient	Cost $/Ton	Min. %	Amount %	Max. %
Yellow Corn	130.00	0.00	**54.71**	100.00
Soybean Meal (48% CP)	290.00	0.00	**30.04**	100.00
Wheat	188.00	4.50	**4.50**	4.50
Corn DDGS	135.00	3.50	**3.50**	3.50
Poultry By-product Meal	225.00	3.00	**3.00**	3.00
Dicalcium Phosphate	960.00	0.00	**1.14**	100.00
Limestone	160.00	0.00	**1.03**	100.00
Soybean Oil	299.00	0.00	**0.74**	100.00
L-Lysine HCL	2400.00	0.00	**0.34**	100.00
DL-Methionine	2667.00	0.00	**0.32**	100.00
Common Salt	50.00	0.00	**0.29**	100.00
L-Threonine	2133.00	0.00	**0.13**	100.00
Vitamin Premix	3600.00	0.10	**0.10**	0.10
Mineral Premix	1060.00	0.10	**0.10**	0.10
Coccidiostat	9700.00	0.05	**0.05**	0.05
Phytase	5333.00	0.01	**0.01**	0.01
0	0.00	0.00	**0.00**	0.00
0	0.00	0.00	**0.00**	0.00
0	0.00	0.00	**0.00**	0.00
0	0.00	0.00	**0.00**	0.00
0	0.00	0.00	**0.00**	0.00
0	0.00	0.00	**0.00**	0.00
0	0.00	0.00	**0.00**	0.00
0	0.00	0.00	**0.00**	0.00
0	0.00	0.00	**0.00**	0.00

TOTAL	100.00

Nutrient	Required	Supplied	Max.	Units
DM	0.00	**87.63**	100	%
M.E.	3.00	**3.00**	100	Kcal/g
Crude Protein	0.00	**22.33**	100	%
True Protein	0.00	**20.12**	100	%
E.E	0.00	**3.69**	100	%
C.F	0.00	**2.42**	100	%
Ca	0.96	**0.96**	100	%
Total P	0.00	**0.73**	100	%
Avail. P	0.48	**0.48**	100	%
Ca:P	0.00	**0.00**	0	-
Na	0.16	**0.16**	100	%
Cl	0.16	**0.23**	100	%
Choline	1.70	**1.79**	100	mg/g
Folate	0.00	**0.50**	100	mg/kg
dLYS	1.28	**1.28**	100	%
dMET	0.51	**0.64**	100	%
dTSAA	0.95	**0.95**	100	%
dTHR	0.86	**0.86**	100	%
dTRP	0.20	**0.24**	100	%
dARG	1.37	**1.37**	100	%
dVAL	0.96	**1.06**	100	%
dLYS:TP	-100.00	**-5.89**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%
Nutrient	0.00	**0.00**	100	%

Figure 2. Optimisation of a commercial broiler starter feed using WUFFDA 2.1 (Pesti et al. 2016).

Feed ingredients are quite variable in safety to poultry. Some ingredients like corn and properly cooked soybean meal are safe and no need to set a maximum inclusion level in formula specification. In comparison, other ingredients can contain some non-nutritive compounds like fibre or anti-nutritional factors (ANF), which can be detrimental to poultry. For instance, cottonseed meal contains gossypol pigments and high fibre which limits its use in poultry feeds because feeding high levels of cottonseed meal has been found to cause egg discolouration and growth depression (West 1955; Heywang, Heidebrecht, and Kemmerer 1965). The high content of glucosinolates in some rapeseed cultivars and pennycress meal were reported to produce toxic effects in poultry (Smith and Campbell 1976; Alhotan et al. 2017). Some cultivars of grain sorghum contain high tannins that interfere with poultry performance (Chang and Fuller 1964). Other ingredients with high fibre contents (e.g. DDGS, sunflower meal) or non-starch polysaccharides (e.g. wheat) can reduce performance when fed at high levels and without enzyme addition, especially for young birds (Kiarie, Romero, and Ravindran 2014). Therefore, a maximum level must be included in formula specifications to ensure that the ingredient does not exceed a safety level.

Feed ingredients prices

Typically, feed represents at least 70% of the total production costs in poultry. Thus, minimising feed costs through strategic ingredient purchasing or considering alternative ingredients is a high priority. It is well known that ingredient prices fluctuate continuously due to a variety of factors such as weather conditions, rising demand from other industries (e.g. swine, biodiesel), global crude oil market, economics (*e.g.* currency exchange rate fluctuations), and policy (e.g. geopolitical instability, import tariffs). Weather is a major factor influencing the global feed supplies as many regions in the world experience drought or devastating rain and floods. The growing demand for the biofuel industry has led some corn producers to ship their crops to ethanol plants for ethanol production, which added some pressure on corn prices worldwide. Feedstuff prices can also be affected by global crude oil prices as high energy prices will increase shipping costs. These factors can make a significant increase in formula costs, leading to increased production costs and poor profit margins. Figure 3 illustrates the fluctuations in corn and SBM prices over the past 12 years in the US markets. To cope with high prices, formulators tend to include alternative ingredients in formulations to minimise costs. However, the costs of alternative ingredients have to be competitive to corn and SBM to be purchased and included in formulas. Sensitivity analysis or parametric LP can help formulators in ingredient purchasing to calculate how much can be purchased at each price (Paulding, Pesti, and Miller 1986). Figure 4 demonstrates the results of parametric cost ranging analysis in which the cost of wheat influences its inclusion in a corn-SBM broiler starter feed. When the price of wheat is greater than 134.4 USD per ton, none should be purchased because there is no economic advantage of feeding wheat. When the price drops down to 134.4, USD then enough wheat should be purchased for a maximum inclusion of 18%. Further reduction in wheat price to 111.6 USD would increase the maximum inclusion to 20.2%. The maximum inclusion of wheat that can be included in this formula ever is 42.7%, and this number can only be arrived at if wheat were available at 97.2 USD or below.

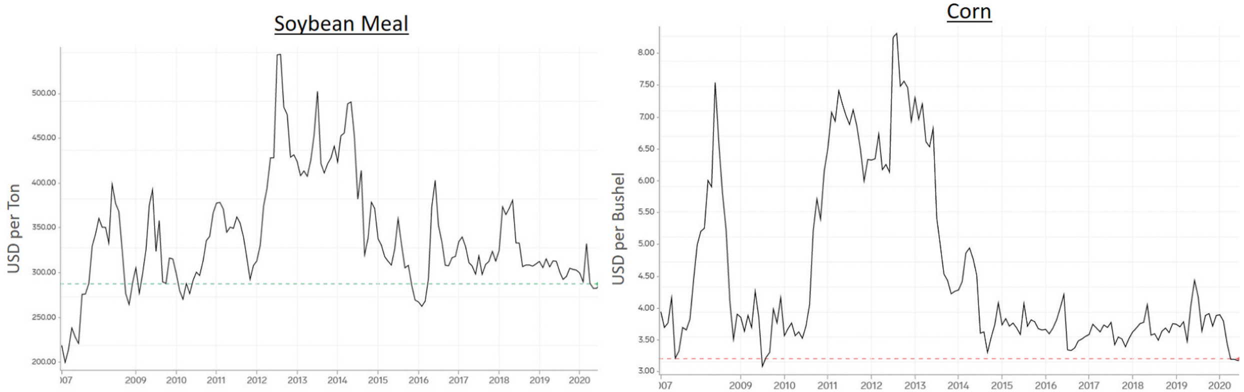


Figure 3. Fluctuation in corn and SBM prices between 2007 to 2020 in the US markets (Business Insider; https://markets.businessinsider.com/commodities).

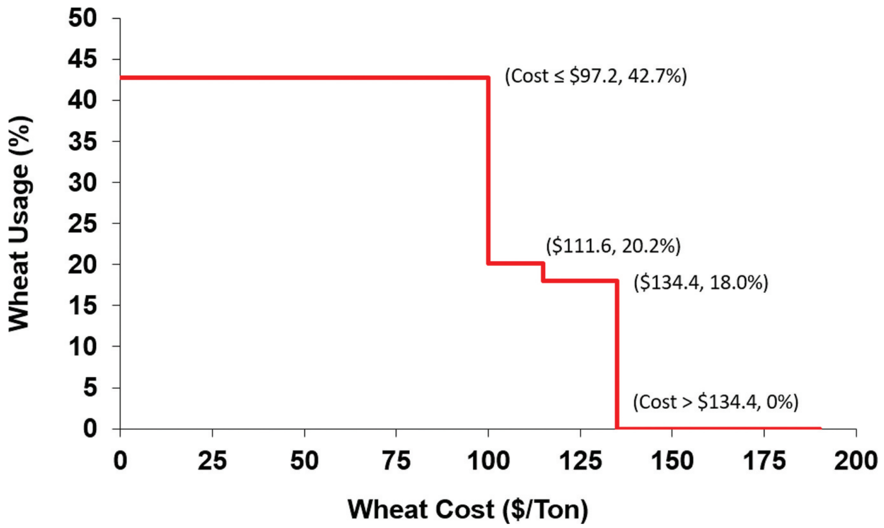


Figure 4. Parametric cost ranging analysis showing the influence of cost of wheat (U.S. $ per ton) on its inclusion (%) in a broiler starter feed.

Nutrient requirements

The concept of requirements indicates the minimum feeding level of a nutrient to achieve a performance goal or to prevent a nutrition-related disease under a particular set of conditions. Figure 5 illustrates how the digestible lysine requirement for growing broiler chicks is estimated by broken line methodology (Pesti et al. 2009). As the dietary lysine level increases, the growth rate increases until reaching the plateau. The requirement can

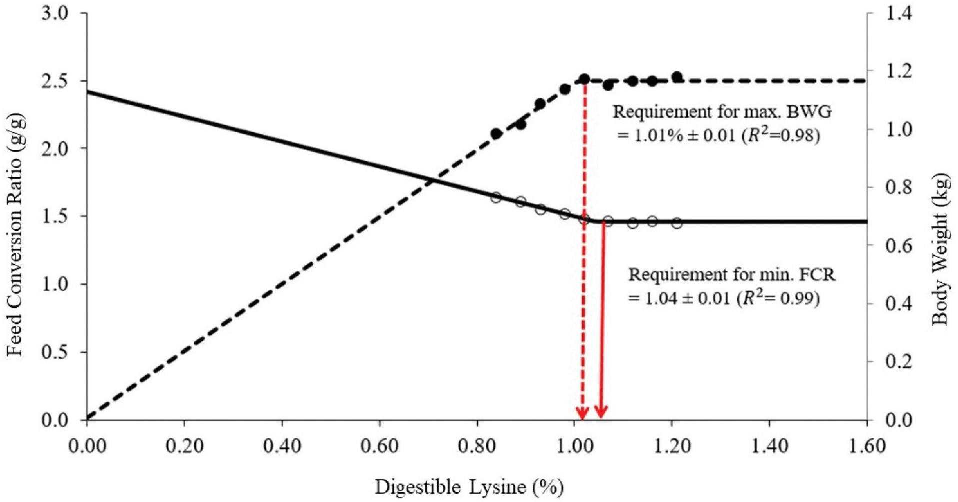


Figure 5. Digestible lysine requirements for maximum BW and minimum FCR as estimated by broken line methodology. Requirement ± standard error of the mean.

then be estimated at the intersection of the two lines. An estimation of 1.01% is the minimum feeding level of lysine for maximum growth under a specific set of circumstances (e.g. specific gender, strain). The producer could also feed higher lysine levels, but there will be add-on costs associated with this decision. There can be more requirements for other criteria (e.g. minimum FCR, maximum breast yield). Figure 5 demonstrates the variation in lysine requirements and shows how the requirement for minimum FCR is higher than the requirement for maximum BW. Usually, the criterion used in nutritional requirement tables is not specified, which might cause some confusion.

Extensive research conducted on nutritional requirements throughout the 20th century had led professional institutions such as the National Research Council (NRC 1994) to compile and publish data on nutrient requirements of poultry. However, publications such as NRC became outdated and inappropriate for modern poultry, which has gone through significant genetic selection since 1994. Currently, other updated sources provide valuable information on requirements such as Cobb Vantress (AR, USA), Aviagen (AL, USA), and Hy-Line (IA, USA). In general, poultry require 37 nutrients (i.e. 10 AA, 13 vitamins, 13 minerals, and one fatty acid) besides water and energy. Energy and AA are perhaps the most important determinants of profitability in poultry production and have received much attention over the past decades.

Energy requirements

Energy is usually the starting point when setting the requirements during feed formulation. Poultry nutritionists are interested in knowing exactly how much available energy is contained in ingredients. In fact, the term 'available energy' is ambiguous when it comes to describing the exact amount of energy available to the birds, and thus the term is practically meaningless. Other scientifically defined terms like Gross Energy (GE), Digestible Energy (DE), Productive Energy (PE), Metabolisable Energy (ME), and Net Energy (NE) have been used to describe the energy contents and partitioning of ingredients (NRC 1994). Among these terms, only the ME is used as a reliable measure of available energy in poultry formulations. The ME is the difference between the GE of feed and excreta. Historically, the PE, which is the energy retained in the body and eggs, was first used in formulations to represent the energy available for production (Fraps and Carlyle 1939, 1942). However, the PE did not consider energy available for maintenance and was unrepeatable due to being affected by many factors (e.g. environmental temperature, bird activity); therefore, it was ignored.

The other method, the ME, then took over and gained popularity among nutritionists because the ME was much easier to measure and repeatable (Hill and Anderson 1958; Hill et al. 1960; Sibbald 1976). The apparent ME (AME) and the true ME (TME), either with or without correction for nitrogen retention (AMEn or TMEn), are the two systems that have been used for poultry formulations. A large volume of AME data has been determined with growing chicks and has been available, making the AME more commonly used than the TME. The TME was first introduced using mature roosters aiming to correct the standard ME values for endogenous losses; thus, it was termed 'true' (Sibbald 1976). In practice, formulators usually rely on published tables for their matrix ME values, use prediction equations based on proximate analysis, use determined values from *in vivo* assays, or sometimes depend on an educated guess from an experienced nutritionist.

However, there have been ongoing debates among poultry nutritionists over the past century on the variability, methodology, and even the terminology of the ME systems. Pesti and Edwards (1983) explained how nutritionists misused the term ME (e.g. labelling the results of similar bioassays differently, ME_n *vs.* AME_n) and how the terms used did not reflect the methodology applied (e.g. test type, bird age). They proposed a subscript system to clarify the discrepancies, but the system was largely ignored. Mateos et al. (2019) reported high variability in tabulated ME values within selected feedstuffs from various sources and explained serious problems that may limit the use of the available prediction equations in feed formulations. Wu, Choct, and Pesti (2020) identified and discussed various flaws about the methodologies applied in the bioassays used in generating the ME data. Bioassay inaccuracy, unnecessary corrections, weak experimental designs, and erroneous mathematical or statistical calculations are among the flaws they detected. Therefore, formulators should use the current available ME values with care when formulating poultry feeds. The TME is not recommended in the formulation of poultry feeds because the assay used includes tube feeding of a single ingredient and fasting birds, which may overestimate the ME (Wu, Choct, and Pesti 2020). The AME appears to reflect the actual available energy in ingredients to growing birds compared to the corrected AMEn; thus, it may be used in formulations instead (Mateos et al. 2019; Wu, Choct, and Pesti 2020).

Protein and amino acid requirements

It is generally accepted that dietary requirements should be for the essential AA not for protein *per se*, which led to eliminating CP from commercial formulations. For maximum growth, birds require 10 essential AA (EAA) plus enough nonessential AA (NEAA) or amino nitrogen to make the NEAA. The introduction of many synthetic AA to the market has helped formulators decrease the dietary levels of CP considerably, resulting in a significant reduction in feed costs and environmental pollution. Nutritionists were concerned if further reduction in CP could bring about more savings and less pollution. However, feeding very low CP diets fortified with synthetic AA to meet the requirements of the EAA only resulted in depressed performance and modified carcass composition in broilers (Sklan and Plavnik 2002; Aftab, Ashraf, and Jiang 2006). When some NEAA such as glycine and serine were added to the low CP diets, the performance was restored, indicating that lowering CP beyond a particular level made the diet deficient in amino nitrogen, leading to insufficient NEAA content (Corzo et al. 2005; Dean, Bidner, and Southern 2006). This observation clearly indicates that chicks require some quantity of NEAA to be present in the diet or at least enough amino nitrogen for the synthesis of NEAA. Aftab, Ashraf, and Jiang (2006), based on a review of the literature, suggested a safe reduction in the dietary CP for broiler chickens by a factor of 10% in the starter (0–21d), grower (21–42 d), and finisher (42–56 d) phases to reach minimum values of 20.7, 18.0 and 16.2%, respectively. These values are in the range of current breeding companies' specifications for the achieved CP in the formula (Ross 308 Performance Objectives 2019; Cobb 500 Broiler Performance & Nutrition Supplement 2018). Recent reports have suggested more reduction the dietary CP with synthetic AA and glycine supplementations and showed that reduced CP in wheat-based feeds is very similar to that in corn-based feeds in terms of the effects on performance (Van Harn, Dijkslag, and Van Krimpen 2019; Hilliar et al. 2020).

Unlike CP, TP is calculated based on nitrogen from AA only and excludes non-protein nitrogenous compounds (NPN) like urea; therefore, the TP is a more accurate representation of AA content in feed than CP. The factor 6.25, which is used to calculate CP, was recommended after finding that some proteins of animal origins such as milk casein contained 16% nitrogen (Jones 1931). Subsequently, the assumption behind the 6.25 states that all proteins contain 16% nitrogen, and in fact, this is not valid because not all proteins contain 16% nitrogen. Furthermore, not all nitrogen in feedstuffs comes from AA as NPN compounds also contribute to the total nitrogen content, and these compounds are not utilised very well in the biosynthesis of NEAA (Heger 2003). Thus, TP should be the most accurate representation of AA in feedstuffs. The TP content can be calculated by multiplying the percentage nitrogen in a sample by specific nitrogen to protein conversion factors derived based on a variety of feedstuffs of plant and animal origins. Sosulski and Imafidon (1990) reported specific factors for 23 foodstuffs such as dairy, meat, cereals, and legumes with an average of 5.68. Mariotti, Tomé, and Mirand (2008) compiled data on plant and animal products and recommended a default factor of 5.60 to replace the 6.25 factor. From a scientific perspective, the use of the universal conversion factor of 6.25 in poultry formulations could overestimate the TP content of feeds; thus, it is inappropriate. (Pesti and Alhotan 2014; Alhotan and Pesti 2016).

Poultry feed formulations for most of the 20th century were done on the basis of total AA. Nutritionists realised early that AA in feedstuffs are not fully utilised by birds. Therefore, a costly margin of safety (MOS) was necessary when feeds were formulated on total AA using high inclusions of ingredients with low AA digestibility to avoid any reduction in performance (Rostagno, Pupa, and Pack 1995; Parsons 1996). In order to meet the AA requirements more precisely, more poultry nutritionists around the world have shifted towards formulating feeds on the basis of digestible AA. The new practice was more efficient as it minimised AA overfeeding, reduced feed costs, and minimised environmental pollution. AA digestibility coefficients used in feed formulations are obtained either using young or adult birds. For the assays involving young chicks, samples of undigested AA are taken from the ileum and may or may not be corrected for endogenous losses (e.g. sloughed cells). As the name implies, the Apparent Ileal Digestibility (AID) assay is not corrected for the endogenous losses; therefore, it can be influenced by the level of feed intake or dietary AA intake, resulting in underestimated digestibility coefficients (Lemme, Ravindran, and Bryden 2004). The True Ileal Digestibility (TID) is corrected for both types of endogenous losses (basal and specific), while the Standardised Ileal Digestibility (SID) is corrected only for the basal endogenous losses (Lemme, Ravindran, and Bryden 2004). The SID has been more popular in feed formulation than the TID because of the large volume of data available. The precision-fed rooster assay involves sampling excreta of mature caecectomised roosters as the test subjects and can be corrected for endogenous losses to get true total tract digestibility coefficients or TTTD (Likuski and Dorrell 1978; Sibbald 1986). It has been shown that the digestibility coefficients obtained from the rooster assay were not similar to those from the chick assay for some ingredients, and considerable differences exist (Ravindran and Bryden 1999; Garcia, Batal, and Dale 2007; Tahir and Pesti 2012).

Consequently, it is better to use the SID coefficients to formulate broiler feeds and the TTTD coefficients for mature birds.

One of the important enhancements in poultry feed formulations in the past few decades was introducing the ideal protein concept in which the AA pattern of the feed is an exact match to the requirements (Baker and Han 1994; Firman and Boling 1998). In the ideal protein concept, the dietary requirements of AA are expressed in ratios to lysine as a reference AA. The logic behind the ideal protein concept is that whenever AA requirements change, the ideal ratios should remain constant because AA are required in ratios to make body proteins. The concept of ideal protein allows nutritionists to adjust AA density of the diet depending on bird genotype, type of production operation (e.g. broiler growers, whole bird integration, portioning integration), and whatever circumstances they might encounter (e.g. rise in input costs, climate). As the dietary AA density is increased for fast-growing broilers, the growth of body fat is decreased while the growth of body protein is increased, with net growth in BW in a curvilinear manner (Jackson, Summers, and Leeson 1982; Corzo et al. 2005). Technically, the producer should expect a heavier and leaner broiler with an improved FCR when feeding high AA density. Reducing the dietary AA density will make feed less expensive, but the bird's productivity will be reduced. On the other hand, increasing AA density will improve productivity, but the feed will be more expensive. In fact, profitability will depend on feed costs and income from sellable products.

Calcium and phosphorus requirements

Calcium (Ca) and phosphorus (P) requirements are routinely expressed on a total and available basis, respectively. The abundance and lower prices for inorganic Ca sources (e.g. limestone) and the low Ca concentrations in plant feedstuffs have delayed the necessity of establishing digestibility values of Ca in various feedstuffs. Phytic acid in plant-based feedstuffs forms complexes with minerals such as P (and Ca), rendering much of the ingested P unavailable to the bird (Singh 2008). Therefore, considering the available P (total P – phytate P) during feed formulation has been a common practice to reflect the P requirement closely. Recently, diet formulation on a digestible Ca and P basis has been suggested to closely meet the Ca and P needs (Adedokun and Adeola 2013). Thus, more research has been conducted on Ca and P digestibilities in poultry (Shastak et al. 2012; Anwar et al. 2016, 2018; David et al. 2019).

Feed formulation challenges

Nutrient variability of feed ingredients

One of the challenges that a formulator might face is the variability in ingredient quality, which can result in under- or over-feeding, leading to environmental pollution, reduced bird performance, and increased input costs. The question that is being asked here is, 'do the matrix values truly reflect the composition of the raw materials in stock?'. If the values in the software database are outdated or obtained from an ingredient composition table, then the answer is most likely 'no' and in this case, the chance of meeting the minimum specifications is only 50% of the time. Nevertheless, when using actual values from the

NIRS approach, for instance, nutrient variation will be significantly minimised, and therefore, nutrient levels in the finished feed can meet the minimum specifications most of the time.

Other solutions have been proposed to overcome nutrient variability. Chung and Pfost (1964) suggested sampling and assaying all incoming ingredient batches to the mill and then separating the batches based on nutrient content into above- and below-average batches. When applying this technique, variation can be reduced by at least 50% (Alhotan, Pesti, and Colson 2014). Nott and Combs (1967) recommended a subtraction of a half standard deviation (SD) from the matrix values as a MOS. The SP was recommended as an effective technique to increase the chance of meeting requirements since the LP does not account for variability (Rahman and Bender 1971). In fact, overcoming nutrient variability and increasing confidence to meet the minimum specifications would add up some cost to the formula. Feeds formulated based on LP without including a MOS are cheaper than those formulated with the same model with a MOS, while the SP formulated feeds with a 69% probability are intermediate in cost (D'Alfonso, Roush, and Ventura 1992; Roush, Cravener, and Zhang 1996).

Uncertainty of metabolisable energy values

Using the correct ME values for ingredients during feed formulation can be challenging. As discussed previously, there has been controversy on the ME terminology, bioassay methodology, tabulated value variability, and validity of prediction equations, which make ME values questionable. For example, in nutrient recommendations' tables offered by some breeding companies, energy is termed only 'MEn' without specifying which ME system is used (AMEn or TMEn).

Continuous genetic improvement of poultry

Poultry genotypes are continually changing since the 1950s. Breeding companies strive to improve numerous traits of economic importance, such as growth rate, FCR, and egg production. As a result, significant improvements have been achieved in modern poultry. For instance, Havenstein, Ferket, and Qureshi (2003) compared the growth of an old broiler strain with Ross 308 broilers in 2001 and found the latter to weigh 2903 g compared to 641 g at 42 d (≈353%). Furthermore, BW of male Ross 308 broilers at 42 d was reported to increase to 2979 g in 2012 and 3136 g in 2019 (Ross 308 Performance Objectives 2012, 2019), which indicates an improvement of 8% since 2001. One of the challenges that a feed formulator may encounter is applying the correct nutrient specifications to modern poultry. Aftab (2019) highlighted this issue and suggested the ratio of essential AA to energy to increase for the modern broilers. More research has to be done on nutrient requirements as poultry genotypes improve continuously by geneticists.

Feedstuff shortages

One challenge that a feed formulator might face when formulating feeds is feedstuff shortage. Typical poultry formulas contain more than 10 different ingredients, and each ingredient has to be available in sufficient quantity in stock before formulating feeds. A modern feed mill can mix a few thousand tons of poultry feeds a day. However, accurate inventory management of such a mill is not an easy task. Several factors can lead to feedstuff shortages, such as market price and availability, human errors, and logistics challenges. The adoption of modern technology could help mills manage inventory more efficiently to avoid any shortages. For instance, using sensors in bins and silos that measure feed levels and send data to inventory management software could become more common in practice.

Ingredient prices fluctuations

Ingredient prices fluctuate, and this can raise some concerns as margins start to tighten. In a dynamic ingredient marketplace, access to real-time ingredient pricing tools is necessary to deal with price fluctuations. Formulators may benefit from strategic ingredient purchasing, alternative ingredients, and repricing. When prices change, the software database should be updated to reflect the market's current ingredient prices. For instance, if a company that formulates and sells finished feeds to customers has a surplus of SBM purchased for 445 USD per ton in its inventory and the market price increase to 450, USD repricing to keep up with the market could bring up more savings to the company.

Antibiotic-free poultry production

Recently, after the complete ban on the usage of antibiotic growth promoters as feed additives in many world regions, feed formulators have been challenged to keep poultry healthy and to prevent any losses in production. According to a recent survey by WATT Global Media's 2020 Poultry Nutrition & Feed (Roembke 2020), many respondents cited the antibiotic-free production as a challenge, which added some additional costs without consistent results from using antibiotic alternatives. They reported increased incidence of coccidiosis, necrotic enteritis, and colibacillosis due to removing antibiotics from the feed. Most of the respondents in this survey reported some alternatives to be useful, such as probiotics, organic acids, phytogenics and prebiotics.

Litter quality and environmental pollution

Poultry performance, welfare, and environmental pollution are substantively linked to litter quality, and litter quality is linked to feed formulation. Inefficient feed formulation could lead to increased N and P excretion, which are regarded as the main pollutants in poultry production (Powers and Angel 2008). In addition, inefficient feed formulation directly influences excreta condition (i.e. wet droppings and sticky droppings) and eventually determines the quality of the litter (Francesch and Brufau 2004). Excessive moisture in the litter can increase the incidence of contact dermatitis (also aggravated by sticky droppings and ammonia), promote the growth of pathogenic bacteria and moulds, and increase ammonia emissions (Ritz, Fairchild, and Lacy 2009; Naseem and King 2018). Making a balance between meeting the nutrient requirements and minimising nutrient excretion can be challenging during feed formulation.

Fortunately, various nutritional strategies could be adapted to maximise nutrient utilisation and minimise nutrient waste, leading to improved litter quality and reduced environmental pollution. The use of exogenous enzymes in feeds such as microbial phytases to reduce P excretion and carbohydrases (mainly xylanase and β-glucanase) to reduce digesta viscosity has shown some beneficial effects (Slominski 2011). In addition, minimising the dietary CP by using synthetic AA, applying the AA digestibility coefficients, and utilising the ideal protein concept during feed formulation could be efficiently applied to minimise N excretion and input costs (Powers and Angel 2008; Chalova et al. 2016).

Future expectations

Poultry feed formulation in the future is expected to maximise profitability, meet nutritional needs more accurately, and reduce environmental pollution for more sustainable poultry production. Feed formulation models are expected to include several enhancements (Pesti and Alhotan 2014). The TP concept will likely be used to account for the NEAA needs during feed formulation. Mathematically, the ratio of lysine (or any other essential AA) to TP is the simplest method to represent the complex relationships between the EAA and NEAA (Alhotan and Pesti 2016). The importance of considering a required level of dietary NEAA is more pronounced in low protein feeds. The NE system may be adapted in place of the ME systems in commercial poultry formulations (Barzegar et al. 2019; Wu et al. 2019). The NE is preferred over the ME because it represents more accurately the real amount of available energy for maintenance and production. The extra-caloric effect resulting from including fat or oil in poultry feeds could be represented by adding features to formulation models (Miller, Pesti, and Chou 1983). Adding fat to feed at specific amounts slows down the passage rate of the GI tract, resulting in better digestibility of all nutrients. This phenomenon affects the utilisation of all nutrients, especially energy and AA, and when accounted for during feed formulation, this should reflect the actual amounts of nutrients utilised by birds. Future formulations should consider profit-maximising techniques, particularly in integrated operations. These techniques should consider all the major inputs and outputs and should include functions for modelling the biological performance of modern poultry. Furthermore, future formulation models are expected to be environmentally-friendly and should include features to reflect the environmental impact of the formula and suggest alternatives as a means to reduce the environmental impact while maintaining the lowest cost possible. Efforts to stimulate the natural defence system to reduce/eliminate the use of antibiotics should be one of the goals of future research and feed formulations.

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