한국가금학회지 제 39권 제 1호, 53∼62 (2012)
Korean J. Poult. Sci. Vol.39, No.1, 53∼62 (2012)
http://dx.doi.org/10.5536/KJPS.2012.39.1.053

Advances and Future Directions in Poultry Nutrition: An Overview

Velmurugu Ravindran†

Institute of Food, Nutrition and Human Health, Massey University, Palmerston North 4442, New Zealand

ABSTRACT In the past, poultry nutrition has focussed on increasing the production efficiency to meet the progress achieved in the genetic potential of broilers and layers. Future directions in poultry nutrition will be driven by not only by the need to maximise biological and economic performance of birds, but also by societal issues (environment, antibiotic growth promoters, welfare, traceability and use of genetically modified ingredients). Key advances in poultry nutrition are discussed and future directions, which can be expected, are highlighted. Given the tightening supply and ever-increasing cost of raw materials, there will be more pressure to extract every unit of energy and nutrients from feed ingredients. In this context, a number of feed additives are expected to play an increasingly significant role. Feed enzymes and crystalline amino acids, in particular, will have a profound effect on future sustainability of the poultry industry. Future nutritional research need to focus on identifying the barriers to effective digestion and utilisation of nutrients and, to achieve this objective, nutritionists must combine their expertise with those of specialising in other biological sciences, including immunology, microbiology, histology and molecular biology.

(Key words : nutrition, feedstuffs, feed additives, poultry)

INTRODUCTION

Poultry industry has advanced remarkably over the past 50 years. In particular, poultry meat production has undoubtedly been the most successful of any animal industry. Production standards of broilers and layers have continually improved over this period, with male broilers currently reaching a live weight of 2.5 kg at 33∼35 d of age and white egg layers capable of producing 330 eggs in 52 weeks of lay. Genetic selection brought about by commercial breeding companies is responsible for bulk (85∼90%) of the improvements in broiler growth and advances in nutritional management have provided 10∼15% of the changes (Havenstein et al., 2003).

The need to achieve and sustain the improvements in genetic potential was the driving force behind the advances in poultry nutrition and, there had been continuous refinement in the nutrition and feeding practices of commercial poultry. Compiling an overview of the advances in nutrition over the past 50 years is a daunting task and beyond the scope of this overview. In this paper, only the key advances in poultry nutrition are discussed and the focus will be on three main categories: (i) to develop an understanding of nutrient metabolism and nutrient requirements, (ii) to determine the supply and availability of nutrients in feed ingredients, and (iii) to formulate least-cost diets that bring nutrient requirements and nutrient supply together in an effective manner. A detailed discussion of the advances in poultry nutrition can be found in Ravindran (2011). The overall aim is precision feeding to lower costs and maximise economic efficiency. In the past, there had been a tendency to over-formulate diets when doubts exist on the availability of critical nutrients (especially amino acids and phosphorus) or if the nutrient requirement was uncertain. This practice is no longer acceptable because this is not only wasteful, but also excess nutrients are excreted in the manure and are ultimately a source of pollution. By 'fine tuning' diets that more closely match the requirements of the bird, the efficiency of nutrient utilisation can be optimised. In this paper, it is not the intention to review the available literature on the progress of poultry nutrition research, but instead to provide a critical overview of past advances and future directions in poultry nutrition research.

MAJOR ADVANCES IN POULTRY NUTRITION

1. Defining Nutrient Requirements

A major challenge in defining the nutrient needs is the fact

† To whom correspondence should be addressed : V.Ravindran@massey.ac.nz

that they are influenced by a number of factors and are subject to constant changes. Nutrient requirements are influenced by two main factors, namely bird-related factors (genetics, sex and, type and stage of production) and external factors (thermal environment, stress, husbandry conditions). Precision in defining requirements involves accuracy at both these levels. Requirements of major nutrients for various classes of poultry are now available and these developments are made possible largely because of increasing uniformity of genotypes, housing and husbandry practices in the poultry industry.

Historically, the industry has utilised the nutrient requirements recommended in the publication by National research Council (NRC). The most recent publication on poultry was in 1994 and now 16 years old, which is a long period given the genetic advances that have been made in both broilers and layers over this period. Currently the recommendations suggested by commercial breeding companies provide guidelines that closely match the requirements of modern bird strains than those recommended by NRC (1994).

Of all the dietary components, the most expensive and critical are essential amino acids and energy. Defining the requirements for the ten essential amino acids poses considerable degree of difficulty, but has been made easier by the acceptance of ideal protein concept. Like other nutrients, the requirements for amino acids are influenced by various factors, including genetics, sex, physiological status, environment and health status. However, most changes in amino acid requirements do not lead to changes in the relative proportion of the different amino acids. Thus the actual changes in amino acid requirements can be expressed in relation to a balanced protein or 'ideal protein'. The ideal protein concept uses lysine as the reference amino acid and the requirements for other essential amino acids are then set as a percentage (or ratio) of the lysine requirement. The ideal protein balance for meat chickens at different growth phases is shown in Table 1.

The advantage of this system is once the lysine requirements under a variety of conditions are determined, the needs of all other essential amino acids can be calculated. This approach has now become an accepted practice in the industry to set the amino acid specifications in feed formulations.

Table 1. Ideal amino acid ratios of meat chickens at three growth periods

Amino acid	1 to 21 days	22 to 42 days	43 to 56 days
Lysine[1]	100	100	100
Arginine	105	108	108
Histidine	35	35	35
Isoleucine	67	69	69
Leucine	109	109	109
Methionine + cysteine	72	72	72
Phenylalanine + tyrosine	105	105	105
Threonine	67	68.5	68.5
Tryptophan	16	17	17
Valine	77	80	80

[1]Recommended digestible lysine requirements for meat chickens during 1 to 21 days, 22 to 42 days and 43 to 56 days are 1.070, 0.865 and 0.745%, respectively (Baker, 1996).

2. Defining Nutrient Composition and Ingredient Quality

The principal role of feed ingredients is to provide the nutrients that can be digested and utilised for productive functions by the bird. Over the years, enormous volume of data has been generated and compiled on the nutrient composition of raw materials. The variability that is inherent to each raw material is also recognised and such variability places pressure on precise feed formulations. Data on variation (or matrixes) are available for the main feed ingredients and applied in feed formulation packages to achieve better precision. A related development is the availability of rapid tests, such as the near infrared reflectance (NIR) analysis, to predict gross nutrient composition and to access the variability in ingredient supplies on an on-going basis.

However, not all of the nutrients in ingredients are available for production purposes and a portion of nutrients are excreted undigested or not utilised. With advances in feed evaluation techniques, data have been accumulating on the availability of nutrients, especially of amino acids and phosphorus, for poultry. In the case of amino acids, a recent development had been the wider use of digestible amino acid concentrations, rather than total amino acid concentrations, in feed formulations (Lemme et al., 2004; Ravindran et al., 2005; Bryden et al., 2009). The use of digestible amino acids is particularly relevant to situations where diet formulations consist of a range of poorly digestible ingredients. Formulating diets based on digestible amino acids makes it possible to increase the range and inclusion levels of alternative ingredients in poultry diets. In effect, this approach improves the precision of formulation, may lower feed cost and ensures more predictable bird performance.

The use of appropriate energy system is a critical issue because of the importance of energy to bird performance and diet cost. Despite its limitations, metabolisable energy (ME) has been the system of choice of describing available energy. Net energy (NE) system, which is a refinement of the ME concept, has received attention from time to time. However, no real progress has been made in determining the NE of raw materials for poultry. To date, only one large data set of empirically determined NE concentrations of feedstuffs for poultry has been published. In theory, NE will more closely describe the energy available in an ingredient for bird's metabolic functions and is more predictive of animal performance (Pirgozliev and Rose, 1999). It is, however, difficult to assay, costly and time consuming, and has limited use in the routine screening of ingredients.

3. Better Feed Formulation

Once the nutritional needs are defined, the next step is to match these needs using combinations of ingredients and supplements. The object of formulation is to derive a balanced diet that will provide appropriate quantities of available nutrients at least cost. Given the range of possible ingredients and nutrients involved, a large number of arithmetical calculations are needed to produce a least-cost diet.

Over the years, feed formulation has evolved from a simple balancing of few feedstuffs for limited number of nutrients to computer-aided linear programming systems. Currently newer systems of stochastic non-linear programme are becoming popular with the commercial availability of this formulation software. Because variability in ingredient composition is non-linear, stochastic programmes address this issue in the most cost-effective manner possible.

A related development is the use of growth models to simulate feed intake and production parameters under a given husbandry condition. Such models are effective tools to (i) compare actual versus potential performance, which can indicate the extent of management or health problems in the flock, and (ii) provide economic analysis of alternative feeding regimens. It must be noted, however, the models are only as good as the datasets used to develop them.

4. Products of Biotechnology in Poultry Feeding

Progress in biotechnology during the past two decades has offered new opportunities to enhance the productivity and efficiency of animals through improved nutrition. Biotechnologies cover a vast field of applications in animal nutrition. Some of these applications are already in use (Table 2) as distinct from others whose potentialities are known but are yet to be commercially applied because of technical limitations and public concerns (Table 3).

The growth in acceptance of feed additives in poultry production over the last two decades has been an extraordinary development. In-feed antibiotics have been thus far the most effective and successful additive used by the poultry industry. One could say that in-feed antibiotics are partly responsible for the performance efficiency currently enjoyed by the industry. However, the recent mandatory or voluntary removal of in-feed antibiotics from poultry diets, spurred by reports of potential antibiotic resistance in humans, is creating a major challenge. As discussed later, a number of alternatives are being tested and researched, but yet to be broadly accepted by the commercial industry.

Another important additive to enter the animal feed market is exogenous feed enzymes, which have evolved from an undefined entity to a well-accepted tool to improve nutrient utilisation (Bedford and Shultz, 1998). The availability of glycanases (xylanases/glucanases) in the 1990's has effectively overcome the anti-nutritive effects of non-starch polysaccharides (NSP) and enabled the increased use of viscous grains in poultry diets (Choct, 2006). Today, the use of these enzymes in wheat and barley-based poultry diets is routine. During the past decade, the use of another enzyme, microbial phytase, in poultry diets is on the increase, in response to concerns over phosphorus pollution from effluents from intensive animal operations (Selle and Ravindran, 2007). Most recently, carbohydrase enzymes such as xylanases, amylases, and glucanases,

Table 2. Examples of some biotechnological applications that are widely used in animal nutrition

Application	Aim(s) of developing the technology
1. New ingredients	Production of microbial proteins as new feed sources in animal feeding (e.g. single cell protein, yeast protein).
2. Designer ingredients	Nutritional enhancement (e.g. high-oil maize, high-methionine lupins) or reduction in the level of anti-nutritive components in common feed ingredients (e.g. low-phytate maize).
3. Feed additives	
a) Antimicrobials	To suppress the growth of harmful bacteria and promote the establishment of a desirable gut flora balance (e.g. antibiotics)
b) Crystalline amino acids	To increase dietary supply of specific amino acid and improve protein balance in diet formulations.
c) Feed enzymes	To improve availability of nutrients (energy, amino acids, phosphorus etc) in feed ingredients by reducing the negative effects of anti-nutritive components (e.g. microbial phytases acting on phytate, xylanases acting on arabinoxylans in wheat).
4. Gut ecosystem enhancers	
a) Probiotics	To promote the establishment of a desirable gut ecosystem through the proliferation of beneficial species (e.g. direct-fed microbials).
b) Prebiotics	To competitively exclude harmful organisms and promote the establishment of a desirable gut ecosystem (e.g. mannan oligosaccharides).

Table 3. Examples of some biotechnological applications with future potential in animal nutrition

Application	Aim(s) of developing the technology
1. Modification of gut microbes	To genetically modify microorganisms naturally present in the gut to enhance their capacity for defined functions or add new functions (e.g. rumen microbes to improve cellulose digestion).
2. Introduction of new gut microbes	To introduce new species or strains of microorganisms into the gut.
3. Bioactive peptides	Improved growth and efficiency (e.g. growth hormone-releasing peptides), improved gut function, immunomodulation, antibacterial properties
4. Antimicrobial replacers	Antimicrobial enzymes (e.g. lysozyme), delivery of specific antibodies via spray-dried plasma and egg products
5. Transgenesis	To modify nutrient metabolism and improve growth efficiency by transfer of genes

as well as other exogenous enzymes such as proteases, are also gaining commercial relevance. Combinations of these enzymes have been shown to be effective even in maize-based diets (Cowieson, 2010), which contain low levels of NSP.

The availability of crystalline amino acids is another major development and this additive has enabled the nutritionists to more precisely meet the ideal amino acid profile and, to improve the performance and yield of high-producing modern birds.

5. Feed Processing

The progress in the technology of feed manufacture during the past 50 years represents a major and necessary development in improving bird performance. The technology has progressed from simple mixing of mash feed to pelleting, which involves various physical, chemical and thermal processing operations (Schofiled, 2005).

Currently, majority of the feed used in the production of broilers is fed in pelleted or crumbled form. Offering feed to poultry in pellet or crumbled form has improved the economics of production by improving feed efficiency and growth performance. These improvements are attributed to decreased feed wastage, higher nutrient density, reduced selective feeding, decreased time and energy spent for eating, destruction of pathogenic organisms and, thermal modification of starch and protein (Behnke, 1996; Amerah et al., 2007).

6. Phase Feeding

Phase-feeding, a form of precise-feeding, is another development during the past two decades. This is a feeding system in which dietary amino acid levels are reduced steadily over time in an attempt to reduce costs associated with excess dietary protein or amino acids. Commercial phase feeding programmes may include several phases to step down amino acids and other nutrients for broilers and layers. The number of phases to be implemented in production cycle is dictated by both economics and the practicability.

The wider implementation of phase/precise feeding, however, is limited by several issues:

- Data on ingredient variation and the reliability of matrix values need to be updated on continuous basis.
- More data on digestible amino acids, at least in the major raw materials, are needed.
- Information is needed on the comparative digestibility of amino acids for different classes of chickens - layers and broilers of different age groups. In particular, it is known that digestibility of various nutrients and metabolisable energy during week 1 is lower compared to older birds (Noy and Sklan, 1995; Thomas et al., 2008; Tancharoenrat et al., 2010).
- Information on metabolisable energy and digestible amino acid requirements for different classes of poultry is seriously lacking.
- Finally, it is unfortunate that we do not have objective rapid tests, which the industry can use to estimate metabolisable energy/digestible amino acids as the raw materials are received at the feed mill.

FUTURE DIRECTIONS IN POULTRY NUTRITION

Future directions in poultry nutrition will be driven by ongoing changes in world animal agriculture and by societal issues. Sometime in the future, we may have to modify feed formulations to accommodate not only science-based needs but also the needs of the society. The impact of social issues (antibiotic growth promoters, environment, welfare, traceability, use of meat and bone meal and genetically modified ingredients) will influence the decision-making from farm level to retail distribution of poultry products (Leeson, 2007).

1. Additives of Interest for the Future

1) Feed Enzymes - Next Generation

In the future, there will be more pressure to extract every kcal of energy and every unit of nutrients. A combination of strategies has to be employed and exogenous feed enzymes will have a key role to play in maximising the release of nutrients. One can expect development of new enzyme products that are effective in range of diet formulations. There is evidence suggesting that preparations with multiple enzyme activities may provide a competitive strategy to improve nutrient utilization in poultry diets (Cowieson et al., 2006; Selle and Ravindran, 2007). Such enzyme cocktails, rather than pure single enzymes, represent the next generation of feed enzymes. This is because feed ingredients are structurally exceedingly complex. In the ‘native’ stage, nutrients in raw materials are not isolated entities but exist as complexes with various linkages to protein, fat, fibre and other complex carbohydrates.

Advances in enzyme technology will continue and one can expect that better forms of enzymes will be developed in the future (Bedford and Partridge, 2001). The ‘next-generation’ enzymes will be close to being ‘perfect’, with high specific catalytic activity (per unit of protein), good thermostability, high activity under wide ranges of gut pH, resistance to proteolysis and good stability under ambient temperatures. Technologies are being evolved to maintain enzymes activity in their dry enzyme products in order to protect them from the heat, moisture and high pressures generated during feed processing and number of thermo-stable enzymes, especially phytases, is now commercially available (Amerah et al., 2011). Given the ever-increasing cost of raw materials and low enzyme costs, there is also considerable opportunity to extract more nutrients with unconventionally high doses of enzymes. In particular, the beneficial effects of super-doses of microbial phytase have been shown to be substantial and consistent (Cowieson et al., 2011).

2) Alternatives to Antibiotic Growth Promoters

The ban in the European Union and different degrees of voluntary withdrawal in other parts of the world on the use of antibiotic growth promoters (AGP) will put extra pressure on the gut health and general health of animals. Currently, there is increasing focus on alternatives to sustain good gut flora and gut health, and potential alternatives include enzymes, probiotics, prebiotics, essential oils, botanicals and organic acids. In the last 10 years, these products have been widely tested and the evaluation will continue in the future.

Exhaustive reviews are available on AGP alternatives and large volume publications are accumulating on their influence in modifying gut microflora profile and animal performance (Partanen and Mroz, 1999; Dibner and Buttlin, 2002; Patterson and Burkholder, 2003; Ricke, 2003; Dibner and Richards, 2005; Gianneanas, 2008; Yang et al., 2009). The scientific literature indicates that the alternatives exert beneficial gut health effects on the host, but the effects of their administration on animal performance are variable. One major weakness is that most scientific data come from studies conducted under controlled experimental conditions that often are not repeated when the products are applied under commercial conditions. Furthermore, AGP alternatives are currently more costly than conventional AGP programmes (Table 4); this is at a time when consumers are demanding lower food prices, coupled to improved quality and food safety.

In summary, most alternatives have been shown to 'mimic' the working effects of AGP on gut flora, none of the current generation of AGP alternatives, on their own, are capable of fully replacing them. This is not to suggest that they should be discounted because they may well have a significant role to play within combination products. For example, there is suggestion that synergistic effects may be expected if probiotics and prebiotics are administered in combination (Roberfroid, 1998).

Table 4. Feed cost of various alternative products, compared to antibiotics and coocidiostats[1]

	Cost, € per ton
In-feed antibiotics	1~2
Anticoccidials	2~3
Enzymes	2~3
Direct-fed microbials	4~7
Acidifiers	3~12
Oligosaccharides	2~15
Botanicals	3~25

[1]From Huyghebaert et al. (2011).

A major problem faced by the commercial nutritionists is that, within each class of alternatives, numerous products are available in the market and their efficacy is variable. There is an urgent need to standardise the methodology to evaluate AGP alternatives and to optimise animal responses varying conditions. As noted by Huyghebaert et al. (2011), the main characteristic of a good AGP alternative is practicality; it must consistently improve animal performance. To achieve this, in addition to the alternatives, combination of other strategies including modifications in husbandry and nutritional management need to be considered to promote gut health and good gut flora (Mateos et al., 2002; Dahiya et al., 2006), and these may include,

- Use of highly digestible pre-starter diets
- Use of lower dietary protein levels and better balance of amino acids
- Use of coarse particle size or whole grain feeding to enhance gizzard development
- Maintenance of good litter quality
- Stocking density, improved climate control etc.

Gut integrity is a neglected aspect of gut health, but is equally important as good microflora balance. Intestinal integrity for commercial poultry can be defined as the maintenance of intestinal health to enable the expression of the full genetic potential for growth and yield, and to fully utilize the dietary nutrients. Normal flora plays an important role in maintaining gut structure, strengthening the gut mucosal barrier and protein metabolism of the gut. In situations where the profiles are shifted by pathogenic flora (e.g. clostridium, coliforms), there is significant damage to the mucosal layer and the barrier function. Coccidiosis is another major cause of poor gut integrity and an effective anti-coccidial programme must be in place. Raw material quality is another contributing factor for poor gut integrity. Substances (e.g. mycotoxins) or raw materials (e.g. fibrous feeds) that can irritate the gut must be closely monitored.

3) Crystalline Amino Acids

Protein is a costly item in poultry diets, so maximising the efficiency of protein and amino acid utilisation is very important. Geneticists have done their part in providing current strains of poultry that are capable of producing protein gain at greater efficiencies than ever before. The challenge to the nutritionists is to sustain these improvements in genetic potential by refining the amino acid nutrition of poultry. In this context, the commercial availability of crystalline amino acids was a major development and, has enabled and will continue to assist the nutritionists,

(i) To more precisely meet the ideal amino acid profile and, to improve the performance and yield of high-producing current strains.

(ii) To use digestible amino acids, rather than total amino acids, as the basis of feed formulations (Lemme et al., 2004). The use of digestible amino acids will become particularly relevant as we start using range of non-traditional alternative ingredients that are poorly digestible. Formulating diets based on digestible amino acids makes it possible to increase the diversity and inclusion levels of non-traditional ingredients, despite the fact that they may contain less than optimal natural amino acid profiles and are poorly digested. This will facilitate the dietary creation of "ideal" protein.

(iii) To reduce dietary crude proteins levels and meet the amino acid requirements more precisely. This will lead to greater efficiency of nitrogen utilisation and protein accretion, eventually lowering the nitrogen output in the manure.

(iv) To develop phase-feeding programmes, wherein dietary amino acid levels are reduced steadily over time in an attempt to reduce costs associated with excess dietary protein or amino acids.

Currently three crystalline amino acids, namely DL-methionine, L-lysine.HCl and L-threonine, are available to the industry at competitive prices. Though somewhat expensive, L-tryptophan can also be purchased in feed-grade forms. Crystalline lysine and tryptophan together in the same product is also now commercially available. Valine and isoleucine, the next limiting amino acids in practical diets, are expected to become available in the near future and may allow further improvements in feed formulation.

In summary, the outlook for crystalline amino acids as additives is arguably better than any time in the past. Amino acid supplements have important nutritional, economic and environmental roles to play in future animal production systems. Concerns, however, have been raised in some quarters about the faster absorption of free amino acids compared to protein-bound amino acids, but available evidence indicate that supplements of limiting amino acids are utilised more efficiently by poultry for growth than equivalent quantities supplied as intact proteins (D'Mello, 2003).

2. Sustainability in Poultry Production

With increasing public interest over environment, the reduction of nutrient excretion in effluents from intensive animal operations has now become a major issue. Not long ago, when feeds were formulated, the main objective was how to supply the nutrients (nutrient input). Today there is much public concern about what comes out of the bird (nutrient output). Animal agriculture, including commercial poultry sector, clearly has a problem of releasing excess nutrients into the environment and it must assume ownership of its impact on environment, especially water quality.

From the nutrition point of view, the most obvious strategy is to feed the bird to match the requirement and to improve the efficiency of nutrient utilisation by the bird, which in turn will reduce nutrient load in the manure. Among the other possibilities to improve the nutrient utilisation efficiency, the use of feed enzymes is most promising.

3. Alternative Raw Materials

It is projected that the global demand for poultry continue to increase over the next decade and such a growth will have a profound effect on demand for feed and raw materials. It is also becoming clear that the requirements for traditional raw materials, both energy and protein sources, cannot be met even with optimistic forecasts. The first strategy available to the in-

Table 5. The major factors limiting the use of new ingredients in poultry feed formulations (Ravindran and Blair, 1991)

Nutritional aspects: Variability in nutrient quality; limited information on the variability in the profile and digestibility of amino acids; high fibre (or non-starch polysaccharide) content; presence of anti-nutritional factor(s); need for amino acid supplementation
Technical aspects: Seasonal and unreliable supply; Bulkiness, physical characteristics; Need for processing (drying/ physical processing/ heat treatment/ chemical processing); Limited research and development efforts
Socio-economic aspects: Competition as human food; poor prices relative to other arable crops (farmer); cost per unit of protein (or limiting amino acids) relative to soybean meal (feed manufacturer); cost of processing

dustry is to evaluate potential new raw materials. The feeding value of a large range of locally available non-traditional ingredients has been extensively researched over the decades in all countries and the literature abounds with enormous volume of published data on this topic. The commercial use of these ingredients, however, has been limited due to constraints imposed by several nutritional, technical and socio-economic factors (Table 5).

Once these non-traditional feedstuffs are characterised, the next step is to examine ways to maximise their value by judicious use of additives such as feed enzymes, supplemental crystalline amino acids etc. Given that high fibre and NSP levels may be limiting the availability of nutrients in most of these ingredients, development of appropriate enzyme combinations targeting the fibre fraction (mannanases, cellulases) will be crucial.

Raw material quality, especially the variability, had always been a major constraint in the feed industry. As feed prices skyrocket, quality control and assurance will become more important and the industry will need to invest on quality issues. Clearly it is not possible to improve the quality of raw materials after the delivery to the mill. It logically follows that any improvement in quality can be achieved done only by working closely with the supplier. This will be relevant for all raw materials, including mineral sources, additives and premixes. The investment on rapid tests for available nutrients (not gross nutrients) will also become urgent. Research is warranted to develop rapid and reliable *in vitro* assays for available nutrients (e.g. metabolisable energy, digestible amino acids) that meet the needs of the feed industry on an on-going basis.

5. Basic Research into Barriers to Digestion

Feed represents the greatest single expenditure associated with poultry production. Though broilers and layers are highly efficient in converting feed to food products among farm animals, still they excrete significant amounts of unutilised nutrients. For example, broilers lose almost 25～30% of ingested dry matter, 20～25% of gross energy, 30～50% of nitrogen and 45～55% of phosphorus intake in the manure. Thus there is considerable room to improve the efficiency of conversion of feed to animal products. Much of the inefficiency results from the presence of undesirable components and indigestibility of nutrients in the feed. For this reason, future nutritional research in poultry should focus on issues relating to identifying barriers to effective digestion and utilisation of nutrients, and approaches to improve feed utilisation. In this endeavour, poultry nutritionists are increasingly combining their expertise with those of specialising in other biological sciences, including immunology, microbiology, histology and molecular biology. Such collaboration across scientific areas should continue in the future and will be necessary for the industry not only to improve production efficiency but also to address issues of food safety, environmental stewardship and bird welfare.

LITERATURE CITED

Amerah AM, Gilbert C, Simmins PH, Ravindran V 2011 Influence of feed processing on the efficacy of exogenous enzymes in broiler diets. Wld's Poult Sci J. 67:29-46.

Amerah AM, Ravindran V, Lentle RG, Thomas DG 2007 Feed particle size: Implications on the digestion and performance of poultry. Wld's Poult Sci J 63:439-455.

Baker DH 1996 Advances in amino acid nutrition and metabolism of swine and poultry. ln: Nutrient Management of Food Animals to Enhance and Protect the Environment, Kornegay, ET [editor]. Lewis Publishers, New York. pp. 41-53.

Bedford MR, Partridge GG (Editors) 2001 Enzymes in Farm

Animal Nutrition. CAB International, Wallingford, UK.

Bedford MR, Schulze H 1998 Exogenous enzymes in pigs and poultry. Nutr Res Rev 11:91-114.

Behnke KC 1996 Feed manufacturing technology: Current issues and challenges. Anim Feed Sci Technol 62:49-57.

Bryden WL, Li X, Ravindran G, Hew LI, Ravindran V 2009 Ileal Digestible Amino Acid values in Feedstuffs for Poultry. Rural Industries Research and Development Corporation, Canberra, Australia. p. 76.

Choct M 2006 Enzymes for the feed industry: Past, present and future. Wld's Poult Sci J. 62:5-15.

Cowieson AJ 2010 Strategic selection of exogenous enzymes for corn/soy-based poultry diets. J Poult Sci 47:1-7.

Cowieson AJ, Hruby M, Pierson EEM 2006 Evolving enzyme technology: impact on commercial poultry nutrition. Nutr Res Rev 11:91-114.

Cowieson AJ, Wilcock P, Bedford MR. 2011 Super-dosing effects of phytase in poultry and other monogastrics. Wld's Poult Sci J 67:225-235.

D'Mello JPF (Editor) 2003 Amino Acids in Animal Nutrition. CABI Publishing, Wallingord, U.K.

Dahiya JP, Wilke DC, Van Kessel AG, Drew MD 2006 Potential strategies for controlling necrotic enteritis in broiler chickens in post-antibiotic era. Anim Feed Sci Technol 129:60-88.

Dibner JJ, Buttlin P 2002 Use of organic acids as a model to study the impact of gut flora on nutrition and metabolism. J Appl Poult Res 11:453-463.

Dibner JJ, Richards JD 2005. Antibiotic growth promoters in agriculture: History and mode of action. Poultry Sci 84:634-643.

Gianneanas I 2008 How to use plant extracts and phytogenics in animal diets. In: The Future of Animal Production. Binder EM, Schatzmayr G [editor]. Nottingham University Press, Nottimgham: 111-129.

Havenstein GB, Ferket PR, Qureshi MA 2003 Growth, liveability and feed conversion of 1957 versus 2001 broilers when fed representative 1957 and 2001 broiler diets. Poultry Sci 82:1500-1508.

Huyghebaert G, Ducatelle R, Immerseel FV 2011 An update on alternatives to antimicrobial growth promoters for broilers. Vet J 187:182-188.

Leeson S 2007 Balancing science versus societal issues in poultry nutrition. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 2:1-5.

Lemme A, Ravindran V, Bryden WL 2004 Ileal digestibility of amino acids in feed ingredients for broilers. Wld's Poult Sci J 60:421-435.

Mateos GG, Lazaro R, Gracia MI 2002 The feasibility of nutritional modifications to replace drugs in poultry feeds. J Appl Poult Res 11:437-452.

Noy Y, Sklan D 1995 Digestion and absorption in the young chick. Poultry Sci 74:366-373.

NRC 1994 Nutrient Requirements of Poultry. 9th revised edition, National Research Council, National Academic Press, Washington DC, USA.

Partanen KH, Mroz Z 1999 Organic acids for performance enhancement in pig diets. Nutr Res Rev 12:117-115.

Patterson JA, Burkholder KM 2003 Application of prebiotics and probiotics in poultry production. Poultry Sci 82:627-631.

Pirgozliev V, Rose SP 1999 Net energy systems for poultry feeds: A quantitative review. Wld's Poult Sci J 55:23-36.

Ravindran V, Blair R 1991 Feed resources for poultry production in Asia and the Pacific. I. Energy sources. Wld's Poult Sci J 47:213-231.

Ravindran V, Hew LI, Ravindran G, Bryden WL 2005 Apparent ileal digestibility of amino acids in feed ingredients for broiler chickens. Anim Sci 81:85-97.

Ravindran V 2011 Poultry feed availability and nutrition in developing countries - Advances in poultry nutrition, Food and Agriculture Organisation, Rome. Italy. http://www.fao.org/docrep/013/al707e/al707e00.pdf

Ricke SC 2003 Perspectives on the use of organic acids and short-chain fatty acids as antimicrobials. Poultry Sci 82: 632-639.

Roberfroid MB 1998 Prebiotics and synbiotics: Concepts and nutritional properties. Br J Nutr 80 (Suppl. 2):S197-S202.

Schofield EK 2005 (Editor) Feed Manufacturing Technology V, American Feed Industry Association, Arlington, VA.

Selle PH, Ravindran V 2007 Microbial phytase in poultry nutrition. Anim Feed Sci Technol 135:1-41.

Tancharoenrat P, Zaefarian F, Ravindran G, Ravindran V 2010

Energy utilisation and digestibility of fats as influenced by the age of broilers. Proc Aust Poult Sci Symp 21:59.

Thomas DV, Ravindran V, Ravindran G 2008 Nutrient utilisation of diets based on wheat, sorghum or maize by the newly hatched broiler chick. Br Poult Sci 49:429-435.

Yang Y, Iji PA, Choct M 2009 Dietary modulation of gut microflora in broiler chickens: A review of the role of six kinds of alternatives to in-feed antibiotics. Wld's Poult Sci J 65:97-114.

(submitted: 2012. 1. 16, revised: 2012. 3. 6, accepted: 2012. 3. 7)