Nutritional strategies to reduce environmental emissions from nonruminants[1,2]

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ABSTRACT: The amount of nutrients (i.e., N, P, Zn, and Cu) and associated odors emitted from production animals into the environment can be modulated by several different nutritional strategies, but their practical application is dependent on costs and biological limitations. In general, nutrient excretion may be reduced by avoiding the overfeeding of specific nutrients or by using nutritional manipulations to enhance nutrient utilization in the animal. Loss to the environment can be avoided by manufacturing and handling the feed in a pelletized form that will minimize waste and improve feed/gain. Other strategies for minimizing nutrient losses include: 1) the development of feeding programs that are specific for sex and strain of the animal; 2) increasing the number of feed phases to better meet the animal's age-related requirements; 3) formulating diets to include the minimal amounts of nutrients required to satisfy production goals; 4) meeting the animal's amino acid requirements; 5) using synthetic amino acid supplements to feed to reduce N emission; 6) using feed ingredients with high digestibility and nutrient bioavailability; and 7) formulating diets based on nutrient availability instead of total nutrient content. Nutrient digestibility of feedstuffs is dependent on processing conditions, genetic characteristics of the grains and oilseeds, and the presence of nutritional antagonists in specific feedstuffs used in the diet. Feed ingredients that lead to odor production can be avoided (e.g., fishmeal and some easily fermentable feed ingredients). Feed additives, such as antibiotics, nonstarch polysaccharides, direct-fed microbials, organic acids, microbial enzymes (i.e., phytase, carbohydrases, and proteases) can be used to increase the digestibility and absorption of nutrients or to modulate the microflora. Finally, a cost factor for the control or disposal of nutrients or odor should be considered in the feed formulation to optimize the various nutritional strategies discussed above. Regardless of biological and economic limitations, significant reductions in nutrient and odor emission from nonruminants can be achieved by appropriate nutritional strategies, but response may differ for swine and poultry.

Key Words: Nutrients, Nutrition, Odor Emission, Pigs, Poultry, Waste Management

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Introduction

Increased regulatory pressures are being imposed on animal agriculture to minimize P, N, Zn, and Cu emissions. The amount of mineral emission from a given animal production facility is the difference between the amount that is fed to the animals and the amount that is retained in the meat, milk, or egg products that are destined for human consumption. Mineral emission poses environmental pollution risks only when the nutrients in the manure produced exceed the amount that can be used locally by crops and pastures. If excess nutrients are applied to the land, they can run off into waterways and water bodies or be emitted into the air, causing disruptions in the ecological balance.

In their review, Williams et al. (1999) listed five basic strategies to reduce mineral emissions from intensive animal production in an environmentally challenged area: 1) reduce animal production; 2) collect and transport animal waste nutrients out of the nutrient excessive areas to nutrient deficient areas; 3) collect and recycle the minerals back through animal feeds, thereby reducing the need to import more minerals; 4) grow crops that consume more nutrients from animal manures and harvest them as grain, forage, or other uses; and 5) improve the efficiency of nutrient use by animals. Among these strategies, improving animal mineral use is the most feasible approach to minimize nutrient emission problems in most geographical areas,

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Table 1. Efficiency of dietary mineral utilization among food animal species (Verstegen, 1995)

Food animal species	Nitrogen	Phosphorus
	Mineral retention, %	
Cattle	15	21.3
Swine	28	26.5
Poultry	33	20.8

although the amount of reduction that can be achieved is biologically limited. Kornegay and Verstegen (2001) reviewed the literature on nutritional methods to reduce environmental pollution and odor in swine. The objectives of this review are to characterize the nutrient emissions from intensive animal production facilities that are critical to environmental safety, and discuss nutritional strategies that enhance nutrient use and minimize the emissions of nutrients and associated odors by poultry and swine.

Emission of Critical Nutrients

Phosphorus. Eutrophication of lakes and streams is the major concern for surface water quality. Surface water becomes eutrophic when mineral and organic nutrients reduce dissolved oxygen to levels that favor plants over animal life. Phosphorus is the limiting nutrient for algae and other aquatic plant growth (Sharpley et al., 1994). Too much P input into a body of water leads to plant overgrowth, shifts in plant varieties, interference with recreational and commercial navigation, discoloration, shifts in pH, clogging of water-treatment plant filters, and a depletion of oxygen upon decomposition of the plants. A drop in dissolved oxygen levels in surface water has deleterious effects on fish populations. Overgrowth of certain blue-green algae is a concern because they produce toxins that are potential health hazards for animals and humans (Kotak et al., 1993).

Although P emission is greatest from ruminant species (64% of total P from food animals), P emission concerns are mostly associated with swine and poultry production because of the intensive nature of these sectors and the concentration of P in the manure. For example, swine and poultry produce about 20% of the total manure produced by U.S. animal agriculture, but they excrete about 36% of the total P produced (Crenshaw and Johanson, 1995). The general efficiency of utilization of dietary P is relatively low (Table 1), and a significant amount of P is contained in litter and manure (Table 2), so there is great potential for improvement. However, high rates of P utilization (>50%) in animals are not possible because of biological limitations.

Nitrogen. Excessive N emissions from animal production adversely influence water quality (both surface and groundwater) and have been deemed responsible for acid rain. Like P, N emission from animal production is a problem when amounts exceed plant utilization and it migrates to water supplies. The problem is also complicated by N emissions as airborne N from animal production facilities. Nitrogen excretion rates from different food animal species in the United States are illustrated in Figure 2. On a national basis, ruminant species emit the greatest amount of N into the environment (71%), primarily concentrated in Texas, Nebraska, Kansas, and Iowa (100,000+ tones/yr). However, nonruminant animal production generally poses a greater risk of N emission pollution because of the intensive nature of the industry, particularly in North Carolina, Arkansas, Alabama, Mississippi, and Georgia (50,000+ tonnes/yr).

The efficiency of dietary N utilization varies among species, and it is dependent upon the degree of protein N digestibility, amino acid N absorption or availability, metabolic N demands, and dietary amino acid imbalance. Poultry are most efficient at utilizing dietary N in the form of protein, followed by swine and cattle (Table 1). These differences in N utilization among species are partly due to the partitioning of N used for maintenance, metabolism, and growth. The efficiency of N utilization decreases as maintenance requirements for N increase; and the larger the body size, the greater the maintenance requirement for N. Moreover, dietary N utilization in ruminants is low because of the complexities of fermentation by rumen microflora.

Losses associated with N metabolism in nonruminants are illustrated in Figure 3. Dietary protein is the predominant form of N entering the body. Digestion of protein begins in the stomach by the combined action of gastric secretions of hydrochloric acid and pepsin and is completed in the small intestines by pancreatic proteases, such as trypsin and chymotrypsin, and by brush border peptidases. These and other digestive enzymes and sloughed-off enteric cells are endogenous proteins, which will contribute to the fecal excretion of N. Typically, for every 100 g of protein consumed, a pig will secrete about 30 g of endogenous protein into the digestive tract. About 25% of these endogenous secretions escape absorption in the small intestine and are passed to the large intestine (Souffrant et al., 1993).

Table 2. Average nitrogen and phosphorus contents of manure samples collected by Arkansas Producers (Daniel et al., 1998)

	Nitrogen	P_2O_5	Phosphorus	N/P_2O_5	Concentration
Broiler litter	56	54	23.6	1.04	lb/ton
Dairy manure	6	4	1.75	1.50	lb/1,000 gal
Swine manure	14	13	5.68	1.08	lb/1,000 gal

Therefore, endogenous losses account for about 8% of the dietary protein consumed. Approximately 15% of the N consumed by an animal is lost in the feces, but this amount can be modified up or down by the degree of protein and amino acid digestibility. About 50% of the N consumed by nonruminants is lost via the urinary excretions (urea in mammals and uric acid in birds) as a product of metabolism. Urinary N losses can be modified by the balance between dietary amino acids and the amino acid requirement for maintenance and growth. In general, fecal and urinary N excretion from poultry and swine account for about 65% of the N consumed, of which about 20% is lost to the atmosphere as volatized ammonia and the balance is deposited into the manure (van Heugten and van Kempen, 2000).

Manure and litter are valuable sources of organic N for crops. Poultry litter is especially valuable as a source of N per unit of litter in comparison to other species (Table 2). After excretion, microorganisms in the manure or soil degrade nitrogenous compounds to produce ammonia as the major end product. Ammonia can enter the environment as a volatile emission or be converted to nitrate by nitrification or to gaseous N by denitrification during storage and after its application as an organic fertilizer. Verstegen and Tamminga (1995) reported that ammonia emission from food animals is significant (Table 3). As a percentage of total N intake, ammonia emission is lowest for poultry and highest for swine, primarily due to the way the manure is handled and land applied. Poultry manure is applied to land as a dry litter, whereas most swine manure is treated in an anaerobic lagoon and the effluent is applied to land by spray irrigation.

Zinc and Copper. Land that has received repeated applications of poultry and swine manure might eventually accumulate excessive levels of Cu and Zn, which are toxic to many plants and some foraging animals. Unlike excess land application of N and P, Zn and Cu remain bound to soil and do not migrate to water supplies except during soil erosion. Therefore, unless Zn and Cu are removed from the land via plant products, accumulation will occur and will eventually result in an unsustainable situation for some crops. Currently, unsustainable crop production due to excessive Zn or Cu accumulation from long-term manure application is isolated to just a few fields. In most cases, proper mineral accounting and nutrient management can avoid excessive Zn and Cu accumulation.

Nutritional Strategies to Enhance Nutrient Utilization

Minimize Feed and Water Waste. Although often overlooked, a significant amount of feed nutrients may end up in manure or litter simply because it was not consumed by the animal. In general, N and P content in the manure will increase by 1.5% for each 1% increase in feed waste. Poor feeder design and positioning and feed form can result in significant animal feed waste, which ultimately ends up in manure or litter. Gonyou and Lou (1998) reported that pigs wasted about 5% of their feed, but up to 20% of feed waste has been reported in some field conditions. Each time a pig leaves a feeder, it spills about 1.5 g of feed. Assuming a pig accesses a feeder 60 times per day, it could waste 90 g of feed/d. Pigs tend to root in their feed, leading to significant feed spillage from poorly designed feeders. Poultry will also waste a significant amount of feed if feeders are overfilled, adjusted too low, or poorly designed (Beyer et al., 2001). Small birds will climb into feeders and scratch out feed, and larger birds will fling feed out with their beaks or bills if the feeder is poorly designed or adjusted. For both swine and poultry, feeders should be designed such that it is difficult for the animal to push the feed out of the feeder. For pigs, the feed level should be managed such that only 50% of the bottom of the feeder is covered. For poultry, the feeder height should be adjusted such that the top of the feed pan is level with the base of the bird's neck, and the feed fill level to only 25% of the feeder pan.

Water is one of the primary nutrients required by all living beings. Water waste does not affect the amount of minerals emitted, but it will adversely affect manure

Table 3. Losses of nitrogen as excreta and ammonia emission relative to nitrogen intake (Verstegen and Tamminga, 1995)

Species	Total N emission	Ammonia emission During storage	During land application	$kg{\cdot}animal^{-1}{\cdot}yr^{-1}$
	/Emission as a percentage of total dietary N			
Beef cattle	94.7	11.6	13.2	5.7
Dairy cows	85.6	10.4	12.0	8.8
Sows + piglets	83.8	12.7	14.1	8.1
Piglets (to 10 kg)	62.5	12.5	10.4	—
Finishing hogs	76.8	14.9	12.5	2.5
Laying hens[a]	75.8	7.6	8.8	0.035
Broilers[b]	69.7	6.3	8.3	0.05
Turkeys[b]	—	—	—	0.4

[a] Laying hens reared in cages and droppings removed by conveyer belt.

[b] Broilers and turkeys reared on litter floors.

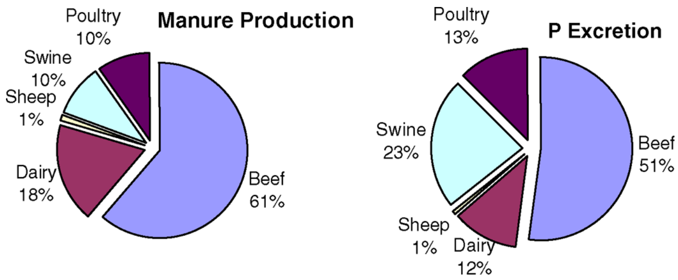

Figure 1. Annual livestock manure production and P excretion in the United States (adapted from Crenshaw and Johanson, 1995).

or litter processing and disposal costs. Although it is a more common problem in swine operations, excessive water waste in broilers and turkeys is a management nightmare, as it requires much more work and bedding material to maintain litter quality. It can also lead to an increased incidence of pests (bacteria, litter beetles, flies, etc.) in the house that can cause flock health problems. Too much water in the house results in excess bacterial growth, ammonia emission, and air quality problems, and it adversely affects the volume and nutrient quality of the litter to be disposed. Excess water use in swine operations places greater demands on the liquid manure-handling system. Therefore, management practices should be followed that minimize water waste. For example, water leaks should be fixed immediately. For poultry, efficient water nipples should be used and water drinkers adjusted to minimize spillage. Drinker rinse water should not be poured on the litter floor after periodic cleaning. Conventional water nipples do not efficiently deliver water to pigs; pigs like to play with nipple drinkers. Installing cups under the drinkers, although problematic to keep clean, will reduce water use. Some of the newer water nipples have been designed specifically to reduce water use (Brumm et al., 2000). Wet-dry feeders are best for minimizing water and feed waste and for improving health and weight gain in swine. Liquid feeding systems allow for accurate control of the feed:water ratio, thereby providing a well-controlled means for minimizing water waste. Den Brok and van Cuyck (1993) demonstrated that changing the water supply from a drinker cup to a feeder with an integrated drink nipple decreased manure production from 1,500 to 950 L/animal placed per year.

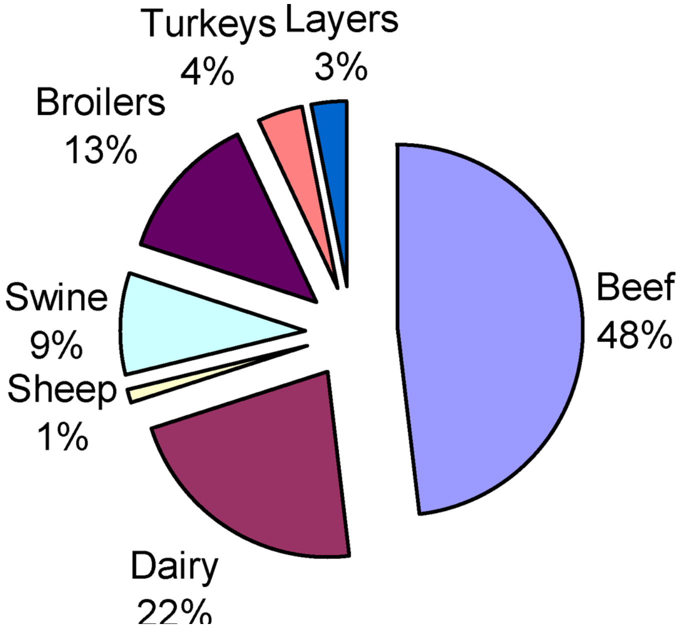

Figure 2. Distribution of N excretion among food animals in the United States (Kerr, 1995).

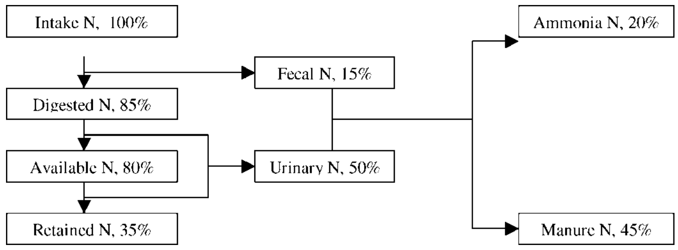

Figure 3. Nitrogen flow in poultry and swine.

Feed Manufacturing. Feed manufacturing technology can have a significant impact on minimizing nutrient emissions from swine and poultry operations by producing the feed in a form that reduces waste and improves the digestibility of the feed. Fine grinding and pelleting feed are effective ways to improve feed use and decrease DM and nutrient excretion. By reducing the particle size, the surface area of the feed ingredient particles is increased, allowing for greater interaction with digestive enzymes. Wondra et al. (1995) demonstrated that a uniform particle size of about 400 μm leads to better nutrient digestibility than coarsely ground material. However, finely ground feed particles may increase esophageal ulcers in pigs (Eisemann and Argenzio, 1999) and can cause gut motility and health problems in poultry (Ferket, 2000). For practical purposes, the feed particle size should be about 700 μm (Kansas Swine Nutrition Guide, 1999).

Manufacturing feed in uniform durable pellets affords significant benefits for both poultry and swine. The pelleting process increases the bulk density and reduces the segregation and dustiness of the feed, thus reducing the losses during handling, transportation, and storage. Feed conversion efficiency of swine and poultry is much improved when they consume pelleted rather than mash feed because it results in less feed spillage during consumption and requires less work of prehension for the animal. Moreover, the heat treatment (steam conditioning, annular-gap expansion, pellet die extrusion) associated with the pelleting process improves feed digestibility by deactivating antinutritional factors and increasing starch gelatinization. Based on a review of the literature, Vanschoubroek et al. (1971) concluded that not only did pigs prefer pelleted feed over mash feed, but feed efficiency was improved by 8.5%, mainly due to a reduction in feed waste. Protein digestibility was also improved by 3.7%. Similar responses were observed in poultry (Beyer et al., 2001). Based on turkey data reported by Brewer and Ferket (1989), there is a loss of about one point in feed conversion for every additional 10% increase in fines in pelleted feed. Expanders, extruders, and extended steam conditioners are used mainly to provide flexibility in ingredient selection and to improve pellet quality and durability rather than to improve nutrient digestibility. Because these machines can expose feed mash to high temperatures, their effect on digestibility depend greatly on the composition of the feed, and digestibility may decrease in some cases.

Formulate Feeds That Closely Match Nutritional Requirements of the Target Animal. In order to avoid and/or minimize mineral emissions, one must first feed the animals according to their nutritional requirements. Over- or underfeeding nutrients relative to requirements will increase mineral emission. Animals will excrete all of the minerals they are unable to assimilate as tissue growth. Therefore, accurate estimates of nutritional requirements are essential to optimize dietary nutrient balance and to minimize mineral emission. Unfortunately, obtaining these estimates is difficult because nutritional requirements are moving targets influenced by many factors in addition to the yearly changes of genetic characteristics. There are several references and models available to estimate nutritional requirements and these models are constantly being evaluated and modified.

The nutritional requirements of poultry (NRC, 1994) and swine (NRC, 1998) have been defined under laboratory-type conditions where animals are well cared for and the environmental conditions are maintained as close to optimum as possible. However, these requirement data are usually not applicable under field conditions where animals are exposed to various environmental and disease challenges. For example, poultry and swine tend to eat less, yet require extra energy for heat dissipation during hot weather than when they are exposed to temperatures within their thermal comfort zone (Waibel and MacLeod, 1995). Therefore, a high-nutrient density diet with a lower protein:energy ratio should be fed when animals are exposed to temperatures above their thermal comfort zone.

The accuracy of nutritional requirement estimates is dependent upon the nutrient. The National Research Council (**NRC**) publications include fairly good minimum requirement estimates for Zn and Cu. However, many animals are fed diets containing greater than 10 times the NRC recommended levels for Zn and Cu because producers observe advantages in health and associated growth promotion. Emission concerns arise from feeding animals high dietary levels of inorganic sources of Zn and Cu to promote growth and health rather than supplying actual nutritional requirements. In order to reduce Zn and Cu emission significantly, use of alternative growth promoters is necessary. These alternatives include antibiotics, pharmaceuticals, enzymes, and organic mineral complexes; however, some of these compounds pose other disadvantages from their use.

Phosphorus requirements are more difficult to define than those for Zn and Cu. Although NRC recommendations are available for all food animals, some estimates are based on a few out-of-date research publications or on unconfirmed models. Mineral requirement estimates are particularly weak for growing and finishing animals, which are the animals that excrete the greatest amount.

Dietary amino acid requirements for animals are continually being evaluated, yet it is the N utilization of animals that still requires the greatest attention because it is complicated by many factors, including genetic growth characteristics, management, and physiological status. Estimates of amino acid requirements for maintenance for growing pigs (Fuller et al., 1989), gestating gilts (Baker et al., 1966a,b,c), and broiler chicks (Leveille and Fisher, 1960; Fernandez et al., 1995) are sparse while estimates for turkeys or layers are absolutely unavailable. The amino acid requirements for growth can be estimated from the amino acid composition of animal output products (i.e., meat, milk, eggs, feathers, etc.). Both amino acid requirements for maintenance and growth change daily as the animal ages.

Estimating Amino Acid Requirements by the Ideal Protein Concept. Understanding amino acid utilization for protein synthesis and maintenance are critical to the formulation of an accurate ideal protein profile and thus for minimizing N excretion. Thus, the ideal protein concept can play an integral role in animal production, particularly as nontraditional protein-containing ingredients become increasingly available. The Illinois Ideal Protein was conceptualized by the early work of Mitchell (1964) and Dean and Scott (1965) and later refined for poultry and swine by Baker and coworkers (Baker, 1997). All of the indispensable amino acids are expressed as a percentage of lysine, which is the reference amino acid. Lysine is a good reference amino acid because good requirement data for most indispensable amino acids other than lysine are not available. Using an established set of ideal ratios of other indispensable amino acids to lysine, it is possible to formulate an ideal protein without having to independently establish requirements for each indispensable amino acid. Baker (1997) clearly explained the application of the ideal protein concept for poultry and swine.

Separate-Sex and Phase Feeding. Even if accurate daily nutrient requirement estimates can be made, they are impossible to fully implement in practice. However, split-sex and phase feeding strategies can optimize the nutritional needs according to changes in age, sex, and growth potential. For split-sex feeding of swine, differences in nutrient requirements among gilts, barrows, and boars should be considered. Barrows typically have

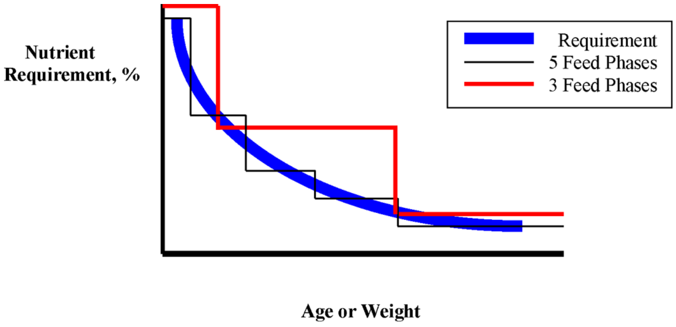

Figure 4. Effect of number of feed phases on nutrient excess relative to nutrient requirement.

a higher feed intake capacity with a lower potential for lean gain than boars, and they should be fed diets with a somewhat lower amino acid concentration (van Kempen, 2000b). Likewise in poultry, females require less dietary protein than males (NRC, 1994), but the cost of gender separation at the hatchery is often not economically feasible unless broilers are raised to the heavier market weights. Split-sex feeding has been a standard feeding practice in the turkey industry for many years because of the large difference if weight gain between hens and toms (Ferket, 2001).

Phase feeding programs match the animal's nutrient requirements as they change with the animal's age or size and reduce the time animals are fed a deficient or excessive amount of nutrients. Figure 4 illustrates the concept of how phase feeding affects mineral emission. Nutrient requirements change daily; thus, animals are fed diets with excess (or deficient) nutrients when only a few feed phases are used, in contrast to when several feed phases are used. Boisen et al. (1991) demonstrated that N excretion could be reduced by 5 to 8% simply by increasing the number of feed phases for growing pigs from two to four (Table 4). For pigs between 25 and 115 kg, changing the number of feed phases from one to two should reduce N and P excretion by 13% (Koch, 1990), while going to a three-phase feeding program should reduce N excretion by 17.5% (van Kempen, 2000b). van der Peet-Schwering and Voermans (1996) reported that multiphase feeding reduced urinary N excretion by 14.7% and ammonia emission by 16.8%. In addition to significant reductions in mineral emissions, feed cost per animal decreases as the number of feed phases increases if performance is equal among all phase feeding programs (Bell, 1998). Increasing the number of phases in poultry feeding programs yields benefits similar to those observed in swine. However, most companies cannot utilize more than four diets for broilers and six diets for turkeys because of feed milling constraints. Some of the new mills have overcome this constraint by blending finished feeds at the point of load-out and by essentially delivering a new feed formulation with every feed delivery to the poultry farm. Using this strategy, one company in North Carolina is able to deliver up to 17 different feed phases to their turkey flocks and thereby minimize nutrient deficiencies or excesses.

A phase-feeding approach could also be used to significantly reduce P emission, since P requirements are closely associated with skeletal development. Because skeletal development decreases substantially as animals grow older, the potential for reducing P excretion increases correspondently. To illustrate this concept, several trials were conducted at the University of Maryland to determine more accurately the nonphytate-P (**nPP**) needs of broilers in a four phase feeding systems (Angel et al., 2000a,b; Dhandu et al., 2000; Ling et al., 2000). The four phases studied were: starter; hatch to 18 d of age; grower, 18 to 32 d of age; finisher, 32 to 42 d of age; and withdrawal, 42 to 49 d of age. In comparison to average commercial usage levels, nPP can be reduced by 5% in the grower diet (18 to 32 d of age) and by 15% in the finisher diet (32 to 42 d of age) without affecting bone strength or performance. Withdrawal-phase (42 to 49 d of age) nPP levels can be reduced by 40%. A subsequent study was done to determine the effects of decreasing the level of nPP in the diet of broilers in the grower, finisher, and withdrawal phases on bone breakage at the processing plant. Results showed that 0.45, 0.36, 0.18 and 0.14% of nPP in the starter, grower, finisher, and withdrawal phases, respectively, resulted in no increase in the number of birds with broken wings or legs at processing in comparison to birds fed industry-average nPP levels of 0.43, 0.36, 0.32, and 0.28% nPP in the starter, grower, finisher, and withdrawal phases, respectively. Therefore, formulating diets based on accurate nPP requirement information can potentially reduce the amount of nPP in broiler feeds, and the amount of P excreted into the litter by at least 10%. Having more accurate P require-

Table 4. Impact of phase feeding and limiting-amino acid supplementation on growth performance and nitrogen excretion of pigs (Boisen et al., 1991)

	Standard protein		Low protein + amino acids	
Pig, 20 to 95 kg	27/23	30/25/21/16	14/10	18/13/9/5
ADG, kg	0.90	0.96	0.92	0.88
Gain:feed	0.43	0.41	0.40	0.40
Lean, %	59.50	57.50	56.20	57.90
Nitrogen excreted, kg	3.40	3.25	2.56	2.48

ment information would also allow us to more fully use feed additives, such as phytase, to decrease P excretion into the litter.

Feed Formulation Techniques

Once nutritional requirements are established, feeds must be formulated as close to the requirements as possible and formulation safety margins must be minimized to avoid nutrient excesses. The accuracy of the feed formulation is dependent upon the following factors: 1) accurate feedstuff nutrient composition data; 2) minimal feed nutrient variability; 3) accurate ingredient weighing and feed batching; and 4) digestible nutrient formulation.

Use Accurate Feedstuff Nutrient Composition Data. The value of a feed formula is only as good as the feedstuffs that go into the formula. Accurate nutrient composition data in the feed formulation matrix is paramount to the formulation of dietary nutrients within specified limits. Use of "book" values, such as those found in NRC (1994; 1998), for routine feed formulation will usually result in feed formulations that do not contain the desired level of nutrients. Frequent and accurate nutrient analysis and quality control measures as ingredients are received at the feed mill are necessary to confirm feed formulation matrix values. Follow-up nutrient analysis of finished feed will then identify problems in the feed mixing and manufacturing processes. Use of near infrared reflectance (**NIR**) technology or other rapid nutrient analysis techniques prior to feed batching could allow for "real-time" feed formulation and significant reductions in safety margins of nutrients critical to environmental safety (van Kempen, 2000a). Other potential applications for NIR are determinations of organically bound Ca and P and determination of feed-mixing uniformity (Mendez et al., 1999). In contrast, many quality control programs at commercial feed manufacturers only measure N (crude protein) and moisture content in feed ingredients. These simple measurements are poorly correlated with available amino acid content of feedstuffs, resulting in greater variation than is desirable for precision nutrition. Reducing this variation by appropriate quality control measures could reduce N excretion by 13 to 27% (van Kempen and Simmins, 1997).

Minimize Feed Nutrient Variability. Ingredient or feed nutrient variability is a hidden cost of feed formulation as well as a liability from a mineral emission perspective. If feed ingredients, and therefore feed nutrients, vary significantly from batch to batch and day to day, then nutrient excesses and deficiencies will occur unless appropriate methods are taken to accommodate nutrient variability. Safety margins commonly placed on top of formulation specifications or matrix values are commonly used to remedy the adverse effects of nutrient variability on the productive performance of animals, and the greater the nutrient variability, the greater the safety margin must be. As formulation safety margins increase, the chances and amount of mineral emission increase. Therefore, the cost benefit of using formulation margins should be optimized relative to the consequences of mineral emissions.

Weigh Ingredients and Batch Feed Accurately. Accurate ingredient weighing and feed batching is necessary to minimize variability in the nutrient composition of feed. Inaccurate ingredient weighing is usually precipitated by the use of the wrong scales for certain ingredients, or using scales that are not precise enough for accurately weighing the call being made on them by the batching computer. Under practical conditions, this problem leads to an increase in weighing variation and overdosing of ingredients (van Kempen et al., 1999).

Formulate Diets on an Available-Nutrient Basis. Animals require nutrients that can truly be assimilated into the body. Therefore, one must consider dietary nutrient availability when formulating diets using precision nutrition techniques. Formulating diets based on chemical analysis may result in greater variability in levels of critical nutrients that are actually available to the animal, which then requires greater safety margins. As mentioned above, large safety margins will result in greater mineral emissions. In contrast, formulation on an available-nutrient basis will allow nutritionists to more confidently formulate diets closer to requirements, especially if food byproducts are used as feed ingredients. Depending on the degree of heat processing, many food and animal byproducts have low or variable amino acid digestibility. Including amino acid digestibility of feed ingredients, unique for each species, is the preferred method used for formulation. The validity of digestibility assays is based on two assumptions: 1) the difference between input and output is a valid indication of overall bioavailability; and 2) digestion is likely to be the rate-limiting step in total amino acid availability. In contrast, minerals (P, Cu, and Zn) are typically formulated on a bioavailability basis using mineral retention levels in critical tissues, namely bone.

Amino acid digestibility assays are done by one of two methods in which the output is measured on either fecal or ileal collections. Amino acid digestibility data for poultry are available using either one of these methods, whereas ileal digestibility values are the only accepted method for swine. The excreta method using precision-fed caecectomized roosters (Sibbald, 1979) is widely used to report true amino acid digestibility values in Canada, the United States, France, and the United Kingdom. Extensive databases of amino acid digestibilities of various ingredients have been reported for chickens (Parsons, 1990) and turkeys (Firman and Boling, 1998). Though the ileal method requires surgical modifications, ileal amino acid digestibility has a distinct advantage over total or fecal amino acid digestibility because ileal amino acid digestibility estimates reflect a point where absorption of amino acids is complete and the potential impact of hindgut microorganisms on the metabolism of amino acids is avoided. In addition, ileal digestibilities partially account for the effects of antinutritional factors, such as tannins (Teeter et al., 1986), gossypol (Tanksley et al., 1981), and trypsin inhibitor (Barth et al., 1993). There is some debate about whether apparent or true ileal digestibility values should be used for formulation purposes. Apparent digestibility measures both the digestibility of the nutrients in the feed and those contributed from endogenous sources within the animal. However, the level of the nutrient in the diet affects this measurement. For example, as the crude protein increases, apparent amino acid digestibility increases. In contrast, true nutrient digestibility values include a correction for endogenous secretions such that they are unaffected by dietary nutrient level. Amino acid digestibility values for swine and poultry are readily available from commercial suppliers of synthetic amino acids.

The bioavailability of P in feed ingredients must be considered to meet requirements for optimal animal performance and avoiding excess emission of P into the environment. About 56 to 81% of the P in cereal grains and oilseed meals that make up the bulk of nonruminant feedstuffs is complexed with the phytate molecule. Phytate-P (**PP**) has low bioavailability in swine and poultry because these animals have low levels of intestinal phytase (i.e., the enzyme needed to cleave the phosphate groups from the phytate molecule). Therefore, inorganic P has to be supplemented to the diet to satisfy requirements. The nondigestible PP and any excessive P added to the diet are excreted in the extreta. Supplementation of feed with a microbial phytase source will increase P availability from PP, and thus the feed should be formulated appropriately to minimize total P excretion.

It is important to clarify terms associated with P bioavailability. “Book” values, such as those found in NRC (1994) for nPP levels in plant ingredients are often referred to as available P (**aP**). This misuse of the aP terminology has led to confusion as to the meaning of these different terminologies. Available P refers to the P that is absorbed from the diet into the animal, whereas nPP refers to total P less PP. Both total and PP can be determined through chemical analysis. Retained P refers to the P that stays in the body (i.e., feed P minus excreta P) and aP refers to P that is absorbed from the diet and is usually determined by subtracting diet total P from ileal total P.

Phosphorus bioavailability of ingredients plays an important role in decreasing excess dietary levels of most nutrients. Inorganic sources of P are generally assumed to be 100% available by poultry and swine. However, studies have shown that inorganic sources of P vary greatly in availability (De Groote and Huyghebaert, 1996; van der Klis and Versteegh, 1996). Monocalcium phosphate has a relatively greater bioavailability than dicalcium phosphate, and deflourinated phosphate has the lowest bioavailability. This is consistent among experimental trials done in the same research unit (Waibel et al., 1984), as well as among researchers (Waibel et al., 1984; De Groote and Huyghebaert, 1996) and between bioavailability assays (Potter et al., 1995). Researchers have found that the experimental conditions under which P availabilities are determined affect absolute P availability results (De Groote and Huyghebaert, 1996), and thus commercial application of these data must be done carefully. The extensive use of absolute P bioavailabilty data (CVB, 1994) in commercial feed formulation in Europe should be questioned, and perhaps a relative bioavailability system should be applied instead (De Groote and Huyghebeart, 1996). Data presented by van der Klis and Versteegh (1996) demonstrate that nPP and aP are not synonymous. These authors found that of the total P in corn, 24% was nPP, but 29% was available to broilers. Similarly, of the total P in SBM, 39% was nPP, but 61% was available to broilers.

Actual P and PP content in different ingredients varies (NRC, 1994; van der Klis and Versteegh, 1996). Data are still limited as to the PP variability within an ingredient and how soil and environmental factors may affect this. Work done by Cossa et al. (1997) showed (in 54 corn samples) a total P content of 3.11g/kg on a DM basis and reported a SD of 0.28 with low and high values of 2.55 and 3.83 g/kg, respectively. Average PP was 2.66 mg/kg (SD of 0.34) with low and high values of 1.92 and 3.54 g/kg DM, respectively. These researchers found no apparent differences between locations and early, medium, and late varieties of corn on the PP content of the corn. There is also limited information on potential variability in the availability of PP (van der Klis and Versteegh, 1996; Cossa et al., 1997) within an ingredient and on how feed manufacturing processes may affect this availability (De Groote and Huyghebeart, 1996).

Improve Feed Digestibility and Nutrient Bioavailability

Nutrients in feedstuffs have different degrees of availability, depending on their digestibility. This is particularly important if feed ingredients having various antinutritional factors hinder nutrient digestibility (Ferket and Middleton, 1998). Nutrient digestibilities in feedstuffs can also be modified by feed processing, by the use of grains and oilseeds genetically modified for higher nutrient digestibility, by dietary enzyme supplementation, and by the use of highly digestible synthetic amino acids and trace minerals.

Adverse Effects of Antinutritional Factors Reduced by Feed Processing. Feed processing techniques that may affect feedstuff digestibility include milling and heat processing. Feed particle reduction affects nutrient digestibility of feedstuffs. As particle size decreases, surface area exposed to enzyme digestion in the animal’s gut increases. Heat processing and steam conditioning can also affect feed beneficially or adversely, depending on the degree of cooking. Adequate heat processing deactivates several antinutritional factors (Ferket and

Middleton, 1998): it gelatinizes starches and breaks some chemical bonds that hinder digestion. In contrast, excess heat processing results in the formation of indigestible complexes (i.e., Maillard reaction complexes of the ε-amino group of lysine with a hydroxyl group of a reducing sugar).

Genetic Modification of Grains and Oilseeds for Better Nutrient Availability. New sources of highly digestible feedstuffs are being developed by crop breeders that will have a remarkable impact on the efficiency of nutrient utilization of nonruminants. Examples of such products are low-phytate or high-aP (**HAP**) corn (Stillborn, 1998) that contains the lpa21 gene. This new genotype contains the same level of total P as normal corn varieties, but only 35% of the total P is PP compared to about 80% in other corn varieties. The P in HAP corn is indeed more nutritionally available to poultry (Waldroup et al., 2000) and swine (Cromwell et al., 1998; Spencer et al., 1998). Other key ingredients are currently being selected for high availability of P. Soybean phytic acid content could be reduced (Raboy and Dickinson, 1993) with a concomitant decrease in PP from 70 to 24% of total P through breeding efforts (Raboy et al., 1985).

Another strategy being implemented is the incorporation of fungal phytase gene(s) into plants such that phytase is expressed at high levels in the seed (Stillborn, 1998). Results from chick trials (Denbow et al., 1998) showed that soybean meal with phytase transgenically inserted and added supplemental phytase were effective in improving PP utilization. Processing is still a concern in terms of inactivation of phytase, regardless of how it is added to the diet. Postexpansion and/or pelleting application of exogenous phytase to feed can be done (Aicher, 1998) thus avoiding heat inactivation of the enzyme. This would not be possible with transgenically incorporated phytase. From a practical standpoint, the use of new ingredients in commercial diets poses some challenges. New ingredients must be identified from planting to actual incorporation into diets, but the logistics and economics of accomplishing this must still be worked out. The simplest solution so far is for feed manufacturers to contract fields for planting specific genotypes. This solution leaves some of the logistical and economic challenges unanswered. In a feed mill, ingredient bin space is always limited, and new ingredients would displace other ingredients.

Supplemental Enzymes Improve Nutrient Availability. The use of supplemental enzymes has great potential for improving nutrient availabilities from feedstuffs and for reducing mineral emissions from animal production. Assuring that the appropriate enzyme blends are properly applied to the feed is essential to reap the benefits of enzyme technology. In a literature review, Ferket (1993) identified four practical uses of feed enzymes to improve nutrient availability: 1) enzymes can increase the availability of storage polysaccharides and proteins that would otherwise be inaccessible to endogenous enzymes; 2) enzymes can break down specific bonds in feedstuffs not usually degraded by endogenous enzymes, thus releasing more nutrients; 3) exogenous feed enzymes can help overcome inadequate digestion of young animals where endogenous enzyme production might be limiting; and 4) some supplemental enzymes break down various antinutritional factors in many feedstuffs, thus increasing the nutritional value.

Dietary Stabilizers of Enteric Microflora. Microorganisms within the gastrointestinal tract affect the growth performance and nutrient utilization efficiency of the host animal. The enteric microflora ecosystem characteristics can affect the morphology of the intestinal lumen, metabolically modify exogenous and endogenous nutrients within the lumen, alter immune function, play an active role in pathogen control, and influence the animal's nutritional requirements (Visek, 1978). If an animal's microflora ecosystem is unstable due to clinical or subclinical pathology, nutrient retention is compromised and mineral emissions increase. Diarrhea and poor feed digestion associated with a destabilized enteric ecosystem also increases odor and manure or litter handling problems. The historically preferred method to stabilize or favorably modify the gut microflora is with feed-grade antibiotics, including the macrolides, fluoroquinolones, β-lactams, glycopeptides, and streptogramins, among others. The practice of feeding subtherapeutic levels of antibiotics to production poultry and swine has been in use since the late 1940s to maintain animal health, improve feed conversion, and increase profitability. Antibiotic agents control the growth and activity of certain microorganisms by interfering with the cellular machinery necessary for cell growth and metabolism, thus decreasing the influence of the microorganism on the host animal. The primary benefits of antibiotic agents are the suppression of subclinical disease and the sparing of dietary nutrients. Indeed, research has shown the positive effects of antibiotic feeding on the digestion of carbohydrates and fats (Eyssen and DeSomer, 1963a,b), the sparing of glucose (Vervaeke et al., 1979), the increased efficiency in the absorption and utilization of calorigenic nutrients (Nelson et al., 1963), and on the improvement of protein utilization (Douglas et al., 1982). The significant impact of these antibiotic growth promoters on reducing nutrient emissions cannot be ignored. Assuming that an antibiotic growth promoter will improve feed conversion by an average of 3%, N and P emission will decrease by about 4.5%.

Competitive exclusion alternatives to antibiotics, such as prebiotic enteric modifiers, have been developed to counter the growth-depressing effects that certain strains of bacteria elicit on poultry. Competitive exclusion is defined as "a process by which beneficial bacteria exclude pathogenic bacteria" within the gut ecosystem (Spring, 1997). Prebiotics are any food ingredients classified as: 1) neither hydrolyzed nor absorbed in the upper GI of the host animal; 2) providing a selective substrate for one or a limited number of host-beneficial bacteria; 3) able to modulate the normal flora in favor of a healthier composition; and 4) inducing systemic or

Table 5. Potential reduction in the excretion of nitrogen and phosphorus by various nutritional strategies in poultry and swine

Strategy	Reduction in nutrient excretion
Formulation closer to requirements	10 to 15% for N and P
Reducing feed spillage/waste	1.5% for all nutrients for every 1% reduction
Pelleting	5% for N, P, Zn, Cu
700 to 1,000 μm (fineness of grind)	5% for N, P, Zn, Cu
Use of highly digestible feed ingredients	5% for N and P
Reduce variability by quality control	10 to 25% for N and P
Reduced protein/amino acid supplementation	10 to 25% for N in poultry; 20 to 40% for N in swine; 9% for N for every 1% reduction in dietary CP
Low-phytate (HAP) corn	25 to 50% for P
Phytase/low dietary P	2 to5% for N, Zn, and 20 to 30% for P
Phytase/HAP corn	2 to 5% for N, Zn, and 20 to 40% for P
Phytase/enzyme cocktails	5 to 8% for N, An, and 20 to 40% for P
Phytase/1,25$(OH)_2D_3$[a]	2 to 5% for N, An, and 20 to 60% for P
Phytase/probiotics	2 to 5% for N, An, and 20 to 40% for P
Cellulases, xylanases, pentosanase, β-glucanase	5% for N and P for appropriate diet
Growth promotion feed additives	5% for all nutrients
Phase feeding	5 to 10% for N and P
Split-sex feeding	5 to 8% for N
Reducing microminerals/organic minerals	Up to 50% for Zn, Cu, Mn

[a] 1,25$(OH)_2D_3$ = 1,25-dehydroxycholecalciferol.

gastrointestinal effects beneficial to the host animal (Gibson and Roberfroid, 1994). Two popular classes of oligosaccharide prebiotics include the mannanoligosaccharides and the fructooligosaccharides, both of which have been shown to improve feed efficiency and the efficient utilization of dietary nutrients such as calcium and magnesium (Baba et al., 1996; Ohta et al., 1998; Parks et al., 2001).

Digestible Nutritional Supplements. Digestible nutritional supplements include amino acids, highly digestible protein sources (e.g., whey, egg white, plasma, isolated soy protein, etc.), highly digestible inorganic P sources (e.g., mono- and dicalcium phosphates, phosphoric acid), and highly digestible organic and inorganic trace minerals supplements. These supplements should be used to balance dietary nutritional requirements and avoid mineral excesses that could increase emissions into the environment. Application costs of these supplements must be considered as with the other methods of reducing mineral emission.

Dietary Modifications to Minimize Nitrogen Emission

Nitrogen Excretion. Assuming protein and amino acid digestibility of ingredients, ingredient quality variation, and the ideal protein (amino acid) requirements are known, significant reductions in N emission can be achieved by reducing the dietary crude protein levels and balancing the digestible amino acid profile requirements with synthetic amino acid. Synthetic forms of the four most limiting amino acids (lysine, methionine, threonine, and tryptophan) are commercially available at a price that is competitive with intact digestible protein costs. According to Lenis and Schutte (1990), the CP level of a typical swine ration can be reduced by 3 percentage points (e.g., from 16 to 13% CP) by replacing soybean meal with synthetic amino acids and corn without negative effects on animal performance. Similar results were observed in poultry (Firman, 1994). Boisen et al. (1991) demonstrated that low-protein diets supplemented with amino acids reduced N excretion by about 24% without affecting growth performance in pigs, regardless of the number of feed phases (Table 4). Kerr (1995) conducted an exhaustive review of over 35 studies of amino acid supplementation in swine and poultry rations and found that N excretion could be reduced from 2.3 to 22.5% for each percentage unit decrease in dietary crude protein. On average, amino acid supplementation of low-protein diets for both poultry and swine reduced N excretion by 8.5% per one percentage unit reduction in CP, regardless of body weight. Schutte et al. (1993) determined that for each percentage point that N is reduced in feed, N excretion is reduced by 10%.

Although low-protein diets can be supplemented with synthetic amino acid to match the theoretical amino acid requirement profile and significantly reduce N emission, it may not always be economically feasible. First, there is a limit to how much dietary CP can be reduced before it starts to adversely affect growth performance and/or meat yield. For example in turkeys, Parks et al. (1996) demonstrated that amino acid supplemented diets with CP at 90% of NRC (1994) reduced N excretion by 16.4% without adversely affecting growth performance, but breast meat yield decreased from 26.5 to 25.5%. This reduced meat yield (a measure of protein retention) could be related to deficiencies in N (Jackson et al., 1983), arginine:lysine imbalance (Veldkamp et al., 2000), or differential efficiencies of synthetic amino acid and intact protein utilization and (Kerr, 1995). Second, the economic feasibility of amino acid-supplemented low- protein diets is dependent upon commodity market prices: The higher the market price for protein (namely soybean meal) relative to synthetic amino acids, the more least-cost feed formulation will favor low protein diets. Ideally, the cost of disposal for manure or litter N should be considered along with least-cost formulation of low-CP feeds.

Ammonia Emission. Ammonia emission is an environmental problem because it has been associated with the nitrification and acidification of rain. Moreover, high ammonia levels in livestock and poultry facilities adversely affect pulmonary health of animals and livestock and poultry workers. The way manure is stored and handled can have a significant effect on ammonia emission, but precision amino acid nutrition and diet acidification can significantly reduce the amount of ammonia emission from animal waste. Ammonia emission can be reduced by feeding low-protein diets with supplemental synthetic amino acids using the precision nutrition techniques described earlier. van der Peet-Schwering et al. (1997) and Aarnink et al. (1993) demonstrated a 10% reduction in ammonia emission by reducing protein by one percentage point. In swine, reducing the pH of urine is the most effective means to reduce ammonia emission because most of the ammonia is derived from urine (Aarnink et al., 1998). Mroz et al. (1996) demonstrated that ammonia emission could be reduced by 30, 33, and 54% by replacing $CaCO_3$ (limestone) in the diet with $CaSO_4$ (gypsum), $CaCl_2$ (calcium chloride), or calcium benzoate, respectively. Urine pH dropped 1.3 pH units with $CaSO_4$ and $CaCl_2$, and 2.2 pH units with calcium benzoate. Den Brok et al. (1997) showed that benzoic acid in the feed decreased ammonia emission by 40%, while also improving feed/gain in market pigs from 2.93 to 2.83. Urine pH and ammonia emission can also be reduced by dietary addition of adipic acid and phosphoric acid, which can substitute for other P sources in the diet (Kim et al., 2000).

Feed Additives to Minimize Phosphorus Emission

As mentioned earlier, typical nonruminant diets contain a substantial amount of PP. Phytate chelates divalent cations, including Zn and Cu, and binds to proteins and starches, making them unavailable to poultry. Kornegay (1996) estimated that P excretion could be reduced by 25 to 50% with the addition of 200 to 1,000 U of phytase. Extensive information is available on phytate and phytase (Nelson, 1967). Phytase and factors affecting its activity and efficiency have been extensively discussed (Nelson et al., 1971; Simons et al., 1990; Ravindran et al., 1995), and thus the focus in this section will be on the potential use of several feed additives together.

Work done by Zyla et al. (1997) demonstrated that, under in vitro conditions simulating turkey intestinal conditions, the use of an enzymatic “cocktail” could release 100% of the PP contained in a corn'soy diet. The enzymatic “cocktail” contained a microbial phytase, acid phosphatase, acid protease, citric acid, and *A. niger* pectinase. From their work, it was clear that phytase alone could not release 100% of the PP present in a corn'soy diet. Only when the right balance between the different components of the “cocktail” was obtained did 100% release of PP from the corn'soy diet occur. To determine whether the enzymatic “cocktail” developed in vitro would work as effectively in vivo, an experiment was done with 7- to 21-d-old turkeys (Zyla et al., 1996). These researchers fed a corn-soy-meat meal diet with a Ca level of 1.2% and an aP level of 0.6% that met NRC (1994) recommendations, a positive control diet containing 0.42% aP and 0.84% Ca (positive control), and diets containing 0.84% Ca and 0.16% aP, to which enzyme preparations (1,000 U of phytase/kg of diet, an enzyme cocktail, or *A. niger* mycelium) were added. They found P retention from 31.0% in the NRC (1994) based diet, 42.8% in the positive control diet, 66.8% in the diet with phytase, 77.0% in the diet with the enzyme “cocktail,” and 79.5% in the diet with the *A. niger mycelium*. Addition of acid phosphatase, pectinase, and citric acid to phytase (enzyme cocktail) also increased P retention.

Other feed “additives” that need to be considered are vitamin D metabolites. Not only does vitamin D stimulate P transport mechanisms in the intestine, it also appears to enhance phytase activity (Mohammed et al., 1991). Vitamin D, as well as its metabolites, 25-hydroxycholecalciferol and 1,25-dehydroxycholecalciferol (**$1,25[OH]_2D_3$**) have been shown to enhance phytase activity (Edwards, 1993; Mitchell and Edwards, 1996). Phytase and $1,25(OH)_2D_3$ appear to act in an additive manner rather than in a synergistic one (Biehl et al., 1995; Mitchell and Edwards, 1996). Mitchell and Edwards (1996) found that the addition of $1,25(OH)_2D_3$ and phytase could replace 0.2% of the inorganic P addition in the diet in 21-d-old chicks. Phytase and $1,25(OH)_2D_3$ alone could each only substitute for close to 0.1% of added inorganic P. Vitamin D metabolites have a clear role in improving P retention and their use with other feed additives (phytase and enzyme “cocktails”) should be considered.

Some *lactobacillus*-based probiotics have been shown to improve growth and feed conversion in poultry and swine. Angel et al. (1999a,b) demonstrated in two studies that broilers fed control diets (19.3% protein and 0.37% nPP for grower; and 17% protein and 0.30% nPP for finisher) and low-nutrient diets (where protein was decreased by 12% and nPP and Ca by 18%) from 18 to 28 d (grower) and 28 to 42 d (finisher) of age had similar performance and bone mineralization when the probiotic was included. Broilers fed the low-nutrient diet had poorer performance than those fed the control and those fed the low-nutrient diet with the probiotic. Birds fed the low-nutrient diets with the probiotic were able to overcome the deficiency exhibited by birds fed the low-nutrient diet without the probiotic. In addition, P retention was 22% higher and N retention was 10% higher in birds fed the low-nutrient diet with the probiotic than in the birds fed the control diet. The addition of the probiotic to the low-nutrient diet allowed broilers to grow as well as those fed a control diet in part because they were more efficient in retaining nutrients. Feeding a low-nutrient diet with the probiotic decreased excreta P by 33% without adversely affecting performance or bone strength.

Nutritional Strategies to Minimize Odor and Dust Emission

Where excessive mineral emissions may lead to environmental pollution problems, odor and dust emission adversely affect the aesthetic and physical quality of life of people living nearby. Odor and dust emission is a much greater problem for the swine industry, but it is also a problem for poorly managed poultry operations. Schiffman et al. (1995) found that people who live near odorous swine operations reported more anger, confusion, tension, depression, fatigue, and less vigor than control subjects did as measured by a scale called Profile of Mood States. Odors associated with livestock and poultry operations come from fresh and decomposing manure (and urine) and spilled feed. Odor perception by neighbors is augmented by dust emission from livestock and poultry facilities because odorous gasses are readily absorbed into the particles, which may easily travel great distances in an air plume. Excellent reviews of odor emission and control were reported by the Swine Odor Task Force (1995) and Sutton et al. (1999).

The most objectionable odors arise from anaerobic microbial fermentation in the gut of animals, in the lagoon, or in litter. Fermentable carbohydrates yield volatile fatty acids, such as butyric acid. Proteins yield volatile fatty acids, phenolics, (e.g., para-cresol and skatole), mercaptans (e.g., hydrogen sulfide and ethylmercaptan), and amines (e.g., putrescine and cadaverine). Therefore, one nutritional strategy to reduce odor emission is to decrease the availability of fermentable substrates for hindgut and fecal microbes by feeding highly digestible feed ingredients and low protein diets (Mackie et al., 1998). Hobbs et al. (1996) reported that finishing pigs fed a least-cost formulated low-protein diet (14.0% protein) decreased ρ-cresol by 43% and other odorous compounds decreased from 40 to 86% in comparison to pigs fed a conventional 18.9% protein diet. Schaefer (1977) reported that ρ-cresol was the main odor-causing agent in swine manure. Similarly, Zahn et al. (1997) reported that C_2 through C_9 organic acids demonstrated the greatest potential for decreased air quality because these compounds exhibited the highest transport coefficients and highest airborne concentrations.

Excessive dust emission in animal and poultry facilities not only augments odor emission problems, but it also can adversely affect the health of livestock and workers. Dust is derived from feed, animal skin, feathers, manure, and bacteria. Feed dust can be reduced by improving pellet quality and adding fat to the pellets after the cooling process. Feed handling equipment should be adjusted to minimize the damage of feed pellets and limit the amount of dust generated, especially inside the production facility. In swine, liquid feeding systems and wet-dry feeders can greatly reduce the amount of dust generated. Skin health can be significantly affected by nutrition, particularly as related to dietary fat quality and Zn.

Implications

In order to increase efficiency, swine and poultry production has become more intensive, causing environmental problems in some geographical areas. Although feed is the primary input source of nutrients, the amount of nutrients ultimately emitted into the environment is dependent on the efficiency of nutrient utilization of the animal. Several nutritional strategies to reduce nutrient emissions from nonruminants were discussed and their potential impact is summarized in Table 5. The impacts of these methods may not be fully additive, but strategic combinations will result in significant reductions in nutrient emissions. The most cost-effective methods that are relatively easy to implement include reducing feed waste, separate-sex and phase feeding, and formulating diets based on nutrient availability. Many of the progressive poultry and swine enterprises have already implemented many of the nutritional strategies, but more research is needed to further refine the applications.

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